Maize - Pigeonpea Intercrop Resource Use Under Semi-Arid Conditions of Kenya.

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DECLARATION

I declare that this thesis is my own composition and, apart from the acknowledged assistance, is a record of my own research. The material has never been presented before to any academic institution for an academic award.

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To my parents, Mr. Daniel Wanderi Mukira and Mrs. Agatha Wangechi Wanderi who are a source of inspiration and my son Daniel.

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ABSTRACT

A field experiment was conducted at Jomo Kenyatta University of Agriculture and Technology between October 2001 and June 2002 to determine light, water and nitrogen use in maize-pigeonpea intercrop system. The experiment was laid out as a randomized complete block design (RCBD) replicated four times. Treatments included two pigeon pea maturity types; two long duration (erect - ICEAP 00053 and semi-erect - ICEAP 00040) and one medium duration (ICEAP 00557) type intercropped with maize (Katumani) or sole crop. Data on canopy light interception, soil water content changes, crop dry matter accumulation, plant total nitrogen and soil mineral N at key phenological stages were determined. Identification of a suitable reference crop to estimate the amount of N fixed by pigeonpea using the difference method was done in a greenhouse experiment. The experimental design was complete block design replicated three times. Maize (Hybrid 511 and Katumani), sorghum (MB30 and IS 25545) and cotton (Hart 89 M and Uka 59/146), were evaluated as reference crops. Sorghum and cotton varieties were also included in the field experiment as reference crops.

Maize and sorghum accumulated more shoot and root dry mass compared to pigeonpea both in the field and greenhouse experiment, hence they were unsuitable to be reference crops. Cotton had similar rooting characteristics and phenological development with pigeonpea. Cotton was a suitable reference crop for the long duration but not the medium duration pigeonpea in the greenhouse and in the field. Long duration cultivars had the highest plant N uptake in the field and contributed high amount of N through litter fall and biological fixation compared to medium duration because of higher biomass production. Soil mineral N increased over time during the growing season, possibly due to N contribution through litter fall. Intercropping maize and pigeonpea showed a better use of light than in sole crop. There was a temporal separation in light use in the intercrop system because maize established faster than pigeonpea, hence utilized light early in the season. Pigeonpea intercepted more light when maize was harvested.

Long duration pigeonpeas extracted more water than medium duration pigeonpea at the depth of 70-90 cm late in the season and maize extracted at 30 –50 cm, possibly indicating that either the long duration pigeonpea had more roots at that depth or the roots were efficient in the extraction of the available soil water an example of spatial separation in water use. Sole maize grain yield in the two seasons were similar (3578 and 3419 kg/ha in season 1 and 2 respectively). Long duration erect pigeonpea had the highest total dry matter hence high yields than long duration semi-erect and medium duration. The average pigeonpea grain yield at the end of the season was 4560, 3203 and 2687 kg/ha for the long duration erect, long duration semi-erect and medium duration respectively. The land equivalent ratio (LER) was 1.23, 1.29 and 1.33 for the long duration erect, long duration semi-erect and medium duration pigeonpea respectively. There was an increase total biomass, maize grain yield and total N uptake from plots that were previously intercropped than plots with continuous maize crop, which indicated the residual benefits of incorporating pigeonpea in the maize cropping systems. This benefit may be through litterfall decomposition and/or N recycling.

CHAPTER 1

INTRODUCTION

1.1 Background information

Declining soil fertility, resulting from continuous cropping with little or no use of organic or inorganic fertilizer application or rotation or intercropping is a major problem in the cereal-based production systems. However in developing countries where farmers are resource poor, the high cost of chemical fertilizers, restrict the use of fertilizers (Bohlool *et al.*, 1992). In the tropics traditional forms of agriculture such as shifting cultivation were once suitable, but now increasing population pressure and exploitation of forests, have turned traditional forms of agriculture into fragile systems, which has aggravated the soil fertility problems. The challenge is to develop sustainable agricultural systems that will meet the present and future needs of rapidly growing population (Giller and Wilson, 2001). Under resource poor farmer conditions, there is need to increase resource use efficiency and farmers income. This may involve intensive cropping with suitable deep rooted leguminous shrubs that can make more efficient use of soil moisture, require less of the purchased inputs like inorganic fertilizer and provide higher economic returns (Rathore *et al.*, 1996).

Legume intercrops are a source of plant N through atmospheric fixation that can offer a practical complement to inorganic fertilizers (Jerenyama *et al.*, 2000) and reduce competition for N from cereals component (Fujita *et al.*, 1992). Legumes also contributes to the economy of intercropping systems by either transferring N to the cereal crop during the growing period (Ofori *et al.*, 1987) or as residual N that is available to the subsequent crop (Papastylianou, 1988).

Intercropping of cereals and legumes could be an option as a means of better utilization of available resources like soil N, moisture and light. However intercropping combinations are often times those that capitalize on both spatial and temporal complimentary, thus resulting in an overall increase in resource use by the system in the growing season (Anders *et al.*, 1996). Complimentarily occurs when component crops use resources differently, examples are given of large yield advantage due to greater light interception over time because of temporal complimentarily between component canopies. Comparable effects may be possible below ground if temporal differences in root growth ensure full use of water and nitrogen during the growing season. Similarly, spatial use of water and nitrogen below the ground could be better by a combination of shallow and deep rooting components (Willey, 1996).

In intercropping the competition for light occurs above ground canopy. Similarly, roots of component crops in intercropping compete for water and nutrients especially nitrogen which is in limited supply in most of the semi-arid areas. However identification of a suitable crop combinations with components differing in root system and canopy architecture is one way of facilitating a more efficient nutrient, water and light management for improved productivity in the intercrop system (Katayama, *et al.*, 1996). Pigeonpea had been traditionally grown as a component of intercrops and may provide an excellent way of spatial and temporal separation of root and canopy and hence would be advantageous in sharing limited resources such as nitrogen, light and water.

1.2 Pigeonpea production in Kenya.

Pigeonpea is the second most important food legume after field beans (*Phaseolus vulgaris*) in the area of cultivation and the leading pulse in semi arid areas in Kenya (Kimani, 1991). Because of its tolerance to drought its production is mainly concentrated in Eastern Province

(Machakos, Kitui, Mwingi, Mbeere, Tharaka Nithi and Meru district), dry areas of Central Province (Kirinyaga, Kiambu, Murang'a and Thika districts) (Kimani *et al.*, 1994) and in the Coast Province.

Pigeonpea is used in more diverse ways compared to other grain legumes. Beside its main use for cooking, dry seeds are crushed for animal feed, green leaves as fodder, stems as fuel wood and to make baskets, huts etc. Pigeonpea leaves are also used to feed silk worms and its dry roots, leaves, flower and seeds are used in different countries to treat a wide range of ailments of skin, liver, lungs and kidney (Nene and Sheila, 1990). Pigeonpea is also used as a boundary live hedge around small farms (Nene and Sheila, 1990). In addition large quantities of pigeonpea are exported from Kenya, Malawi, Mozambique and Tanzania.

In Kenya pigeonpea is commonly intercropped with maize, sorghum, beans and cowpea by small-scale subsistence farmers. Because of their long duration the traditional cultivars are grown as intercrops with shorter-duration crops. The later are harvested at their maturity. The fields are then left to pigeonpeas to grow on residual moisture and are harvested after 220-280 days (Nene and Sheila, 1990). The plants may be left in the field to re-grow and provide browsing for animals. Short and medium duration pigeonpeas, which take three to four and five to six months respectively, to mature, have been introduced in Kenya (Kimani *et al.*, 1994) and provides farmers with greater flexibility and options.

1.3 Factors affecting pigeonpea production

Pigeonpea yields in East Africa are usually low (450-670 kg/ha) although higher yields of up to 2600 kg/ha have been obtained in farmers field. The low yields have been attributed mainly to; low yielding cultivars, unavailability of certified seeds, insect pests, diseases (such as wilt and powdery mildew), poor management practices (low plant densities, weed competition), social economic factors (poor markets) and environmental factors (mainly frequent drought) (Kimani *et al.*, 1994).

Pigeonpea maximizes the use of the limited available water and also conserve moisture and hence postpone drought through a number of mechanisms. These include deep and extensive root system (Sheldrake and Narayanan, 1979), which provides access to water stored deep in the soil profile when that in the surface layers is depleted. Late maturing genotypes have deeper roots than earlier genotypes (Lawn and Troedson, 1990). The combination of drought tolerance and polycarpic flowering habit enable pigeonpea to survive a period of water deficit during which all reproductive structures are shed, and then re-flower and set a new crop once the stress is relieved (Troedson *et al.*, 1990).

Temperature is another environmental factor that influences pigeonpea growth. High temperatures hasten germination, increases leaf area, plant height and shoot dry weight (Troedson *et al.*, 1990). Plant height of all duration pigeonpeas decrease with decreasing temperature (Silim *et al.*, 1995). Medium duration pigeonpea types have an optimum temperature for flowering at 22-24°C with higher or lower temperatures delaying flowering.

1.4 Pigeonpea contribution to soil fertility

Pigeonpea provides several benefits to the soil in which it is grown. It fixes atmospheric nitrogen symbiotically with native rhizobia and leaf fall at maturity adds to the organic matter in the soil and nitrogen (Nene and Sheila, 1990). In an experiment where maize followed pigeonpea, the residual nitrogen was estimated to be approximately 40 kg/ha (Kumar Rao and Dart, 1981). The amount of nitrogen fixed by pigeonpea depends on the method of analysis and the maturity group of pigeonpea. Long duration varieties fix more nitrogen than early maturity groups (Kumar Rao, 1990). The extensive root system breaks the plough pans, thus improving soil structure and allows for optimum moisture and nutrient utilization. Extensive ground cover by pigeonpea prevents soil erosion by wind and water, encourages filtration, minimizes sedimentation, and smothers weeds.

Pigeonpea seems to have special mechanisms to extract phosphorous from some soils (e.g., vertisols) to meet its needs (Nene and Sheila, 1990). Growing of pigeonpea as an intercrop with cereal crops increases the available phosphorous (P) pool of the entire cropping systems by converting the unavailable soil phosphorous reserves into a form available to other crops more efficiently than most crop species (Johansen, 1990). Consequently succeeding crops in the rotation have access to phosphorous and nitrogen from pigeonpea residue. Sorghum plants show improved rooting when intercropped with pigeonpea and have higher yields. Trials on infiltration in plots with sorghum following pigeonpea have shown to be greater than in plots of continuous sorghum cropping. Furthermore, sorghum suffers less water logging damage when grown as intercrop with pigeonpea than when grown as a sole crop.

1.5 Problem statement and justification

Nitrogen is one of the major nutrients that limit crop production in Kenya because of high demand by crops and off-farm export through crop harvests (Giller *et al.*, 1997; Sanchez *et al.*, 1997). Farmers rarely use chemical fertilizers and some use inadequate quantities of farmyard manure in pigeonpea based production systems. Organic sources of N are a practical soil fertility remedial option for small-scale farmers but are not available in large quantities (Kapkayai *et al.*, 1998). Nitrogen inputs through biological fixation can help maintain soil nitrogen reserves as well as substitute nitrogen fertilizers to attain higher crop yields (Provrov *et al.*, 1998). Therefore use of leguminous crops (i.e. pigeonpea) in rotation or intercrop with food crops replenishes soil N through atmospheric nitrogen fixation and litter decomposition (Giller *et al.*, 1997; Silim *et al.*, 1995) and avails extra N in the low input production system.

Pigeonpea restores fertility of soils that are low in nitrogen through biological N fixation and litter fall decomposition and increases yields of cereals like maize, cotton, sorghum or millet when intercropped or grown in rotation (Kumar Rao, 1990). The suitability of pigeonpea for intercropping lies in its initial slow growth, when as an intercrop, a companion crop with a fast initial growth phase completes, most of its growth and development during the lag phase of pigeonpea; thereby minimizing competition for resources (Sheldrake and Narayanan, 1979). Advantage of growing legumes in mixtures result from many factors in addition to possible benefits like efficient capture and use of resources for growth such as light and water (Willey *et al.*, 1981) and addition of symbiotic atmospheric nitrogen fixation. However, it is difficult to measure the amount of nitrogen fixed by pigeonpea in the field because it is deep-rooted crop and grows for a long time. One of the cheapest method to measure the amount of N fixed is the N difference method which involves measuring the uptake of N in the N fixing plant and in the non-fixing plant (reference crop) grown in the same soil (Giller and Wilson, 2001). There is need therefore, to identify a suitable reference crop that will have similar rooting patterns and phenological development as pigeonpea.

Intercrops complement each other in their exploitation of the environment e.g. rooting to different parts of soil thus exploiting different parts of the soil or by having leaf canopies at different lengths which might increase total amount of light intercepted (Willey *et al.*, 1981). Complimentarity of resource use in the intercrop occur either spatially (e.g. crops of different rooting depths) or temporally (e.g. crops of differing phenology or physiology (Fukai and Trenbath, 1993). An understanding of the complimentarity of pigeonpea and associated crops, in moisture, nutrients (especially nitrogen) and light use is paramount to achieving higher productivity in the intercropping system. Such information is useful in the development of management strategies that would improve the productivity and sustainability of the system.

1.6 Objectives

The general objective was to determine and quantify the advantage of growing pigeonpea intercropped with maize in terms of light, water and nitrogen use.

The specific objectives were:

(a) To identify a suitable reference crop for estimation of the amount of N fixed by pigeonpea.

(b) To determine light, water and nitrogen use of medium and long duration pigeonpea intercropped with maize.

(c) To determine the residual effect of pigeonpea on subsequent maize crop.

1.7 Hypothesis

(a) Reference crops have the same rooting characteristics, nitrogen uptake patterns and phenological development as pigeon pea.

(b) There is a spatial and temporal separation in water, nitrogen and light use by pigeonpeas and maize intercrop, which is not influenced by pigeonpea growth habit.

I. Medium duration pigeonpea intercropped with maize are likely to fix similar or more nitrogen compared to long duration pigeonpea over the same growing periods.

II. The water use efficiency of long duration pigeonpea is likely to be higher than that of medium duration pigeonpea.

(c) Maize grown after pigeonpea is not influenced by pigeonpea in the previous season.

CHAPTER 2

LITERATURE REVIEW

2.1 Ecological requirements of pigeonpea

Pigeonpea is a crop well adapted to marginal conditions and non-responsive to inputs. It is a low altitude crop that grows from 0-2000 m above sea level. It is a short day flowering crop and it does well in warm and frost-free areas. Pigeonpea is grown on a wide range of soil types of varying physical and chemical characteristics, major soils being alluvials, vertisols and alfisols with a pH range of 6.5 – 8.5.

2.2 Pigeonpea development and growth

2.2.1 Germination and seedling growth

Germination of pigeonpea is hypogeal, and emergence generally occurs more slowly than in epigeous species such as cowpeas, mungbean, and soyabean. Perhaps because of its hypogeal germination, pigeonpea emerges well from depth (Lawn and Treodson, 1990). Under suitable conditions the seedlings appear above the ground in about 5-6 days (Reddy, 1990). The growth rate of pigeonpea seedlings is relatively slow (Sheldrake and Narayanan, 1979), a potential advantage where pigeonpea is intercropped with a rapidly growing cereal such as maize or sorghum.

2.2.2 Root growth

The root system in pigeonpea consists of a deep, strong, woody taproot with well-developed lateral roots in the superficial layers of the soil (Reddy, 1990). Root system is closely related to plant habit; tall, upright genotypes have a deeper root system than spreading, bushy, genotypes, which have shallower, more spreading and denser root system (Kay, 1979). Regardless of soil moisture distribution, 70% of root biomass and 50% of root length are commonly found in the top 50-cm of the soil (Lawn and Treodson, 1990).

2.2.3 Height, branching and habit groups

Plant height is influenced by maturity duration, photoperiod and temperature. Late maturing, long duration cultivars are generally tall, because of their prolonged vegetative phase. Similarly the short-duration or early maturing varieties are short due to their short vegetative growth phase (Reddy, 1990). Varieties differ greatly in the number and angle of their branches. Based on the angle of branches pigeonpea varieties have been grouped into different classes, erect (30-40^{o}), semi-erect (40-50^{o}) and spreading (60-70^{o}). However, the semi-erect types are reported to possess higher branching habit and plasticity than the compact and spreading types. This makes the former types more suitable for intercropping systems (Reddy, 1990).

2.2.4 Days to flowering and maturity duration

Days to 50% flowering and maturity duration in pigeonpea are highly positively correlated. Days to 50% flowering by a variety vary from location to location and season to season (Reddy, 1990). Maturity duration is a very important factor that determines the adaptation of varieties to various agro climatic areas and cropping systems (Sharma *et al.*, 1981). A broad maturity classification of early (< 150 days), medium (151-180 days) and late (> 180 days) has been reported (Reddy, 1990). Photoperiod and temperature exert profound influence on time to flowering and maturity duration in pigeonpea. Other factors such as soil moisture status and nutrition also influence maturity duration.

2.2.5 Canopy development in relation to light interception and leaf area index.

Leaf area index determines canopy productivity through the amount of solar radiation intercepted. Under favorable conditions leaf area index (LAI) increases exponentially until the canopy starts to close, at which time the older shaded leaves begin to senesce and abscise, but invariably declines during late reproductive phase as assimilates are remobilized into pods and seeds (Lawn and Treodson, 1990). LAI ranges from 4.0-6.0, but can vary widely depending on genotypic characteristics (particularly phenology), environmental factors (particularly water regimes and temperature) and sowing density (Lawn and Treodson, 1990).

Solar radiation is the major resource determining growth and yield component crops of intercrops when other growth resources such as nutrients and water are not limiting (Soetedjo *et al.*, 1998). Intercepted radiation is the difference between solar radiation received at the surface of the canopy, and that transmitted to ground, and therefore it includes the fraction of incoming radiation reflected from the canopy (Squire, 1990). The rate of dry matter production is proportional to the total amount of the incoming radiation that is intercepted and the efficiency with which it is converted to dry matter by the canopy (Squire, 1990). During reproductive phase, the inter-relationship between leaf area index and the proportion of the PAR intercepted by the canopy becomes less apparent as floral structures and developing pods intercept an increasing proportion of the incident radiation. The interception of radiation depends on both leaf area index and canopy architecture which is influenced by leaf size, shape, orientation and spatial arrangements of leaves which can be altered by genotypic effects, water status and spatial arrangement of plants (Campbell and Van Evert, 1994). Plant architecture influence canopy structure, thereby influencing the efficiency of solar radiation interception and subsequent dry matter production (Zaffaroni *et al.*, 1989). In addition to canopy architecture, differences in k (light extinction coefficient) values are also attributed to other factors including differences in overall plant height (Edmendes and Laffile, 1993) and leaf number (Dwyer *et al.*, 1992). For most canopies in moist conditions, fractional PAR interception (f) may be related to LAI (L) by the expression (Squire, 1990);

$$F = 1 - e^{-kl}$$ **Equation 1**

Where, k is the light extinction coefficient.

Rearranging equation above, k can be determined as the slope of linear regression,

$$K = ln(1 - f)/L$$ **Equation 2**

The light extinction coefficient is a dimensionless parameter that represents the fraction of incident PAR intercepted by the unit leaf area and is the indicator of the canopy architecture. As the fraction of the solar radiation intercepted by a given leaf area, increases, k also increases. The extinction coefficient (k) ranges from 0.3-1.3 for the majority of leaf canopies (Squire, 1990). In canopies where the leaf inclination (angle formed between the long axis of the leaf and the horizontal) are nearly vertical (e.g. in many grasses) light penetrates to the lower leaves readily and k is often low, about 0.4 (Nobel *et al.*, 1993). Canopies with most leaves in the horizontal plane are termed as planophiles whereas canopies in which the leaves are close to the vertical are termed as erectophile (Squire, 1990). K values are lower for erectophile canopies and higher for planophile canopies (Campbell and Van Evert, 1994).

In the intercrops changes to pattern of crop development and radiation interception can occur. In the common pigeonpea/cereal intercropping system (e.g. pigeonpea/maize) the canopy of the cereal develop more rapidly and is relatively unaffected by the intercrop, whereas the pigeonpea canopy is shaded and its growth is substantially reduced and its able to tolerate the sudden change from shade to full sunlight when the cereal is harvested (Lawn and Troedson, 1990). However, research to explore the opportunities for exploiting the physiological traits, which assist in the intercrops, needs to be enhanced.

2.3 Water use and water use efficiency (WUE)

Water is a factor that most limits crop production in arid and semi-arid areas (Droppelmann *et al*. 2000). The main effect of water deficit on productivity in pigeonpea can be summarized in terms of the partitioning of biomass to seed (Lawn and Williams, 1987). Water deficits can reduce efficiency of solar radiation interception, through reduced LAI, because of slower rates of leaf initiation and /or smaller leaflets and /or reduced leaf area duration, faster leaf senescence and decrease in k as a consequence of paraheliotropic leaf movement and leaf rolling (Muchow, 1985). Reduction in solar radiation conversion efficiency can be induced through slower carbon exchange rates, presumably because of reduced stomatal conductance, but perhaps also because of direct effect on photosynthesis (Lawn and Treodson, 1990). Reduction in assimilate partitioning efficiency; reflected in lower HI, can arise because of the duration and/or rate of reproductive growth is reduced, or because of excessive abscission of pods and seed sinks induced by a severe stress (Lawn and Treodson, 1990).

Pigeonpea has a reputation as a crop well adapted to drought prone environments. The following attributes contribute to this adaptation. These includes low epidermal conductance, stomatal closure, leaf rolling and paraheliotropic leaf movements, low leaf development rates, leaf abscission, all contribute to reduced energy interception and /or slower rates of water loss, and prolong the period the plant can survive on a limited water supply (Troedson *et al*., 1990). The deep-rooting ability of pigeonpea is a particularly important factor enhancing the plant ability to make most effective use of stored soil water. Greater availability of soil water in the deeper soil layers during the start of the dry season advantagous for long duration crops that have an indefinite growth habit (Astatke *et al.*, 1995). Deep-rooted legumes are also more suitable for combination with cereals such as maize in the intercrop due to phenological differences between the two-crop types (Astatke *et al.*, 1995) therefore temporal separation in water use.

Water use efficiency is defined as the amount of dry matter produced per unit of water lost in both transpiration (T) and evaporation (E) (Sinclair *et al.*, 1984). The relationship between crop yield (total dry matter) and water supply may be expressed as (Bolton, 1981; also cited by Mburu, 1996).

$$WUE = \frac{Y}{ET} \qquad \textbf{Equation 3}$$

Where WUE is water use efficiency (kg/ha/mm)

Y is total dry matter yield in (kg/ha)

ET is evapotranspiration (mm)

It is difficult to determine accurately crop transpiration under field conditions and therefore most research has tended to describe water use efficiency on the basis of ET which can with assumption, be deduced from changes in the water content of the profile.

A simple budget of water content changes into and out of a soil profile is (Pilbeam *et al.*, 1995);

$$P = T + E + R + D + S \qquad \textbf{Equation 4}$$

Where; P is the precipitation (rainfall + irrigation), T is the transpiration, E is evaporation from the soil surface, R is runoff, D is drainage and S is change in storage in the soil profile.

Higher water use efficiency due to reduced soil evaporative loss meaning that crop yields can be maintained at slightly lower available soil water (Steiner, 1994). The balance of water loss may be altered in favor of transpiration, by reducing losses through direct soil evaporation and drainage (Pilbeam *et al.*, 1995). Effective use of rainfall in a cropping system requires that the volume of water transpired by the crop is maximized, because crop productivity is proportional to the volume of water transpired by a crop (Sinclair *et al.*, 1984). The choice of the crop may also influence effective water use because of species differences in both root and shoot growth. For example, chickpea grown at Jindiress, Syria (Brown *et al.*, 1989) extracted water less rapidly than barley (Brown *et al.*, 1987) because of smaller leaf area and less extensive root system, with the consequence that more water was lost through evaporation from the soil surface.

Interçropping increases water use efficiency because of windbreak effect of taller plants such as cereals on shorter plants such as the common grain legumes (Steiner, 1982). Complimentarity use of soil resources by intercrops is another reason for better WUE whereby interference of root systems of the component crops is minimized by exploiting water from different soil layers (Willey, 1979).

Increasing soil fertility could enhance early leaf area development and decrease evaporation (Cooper *et al.*, 1987; Allen, 1990). Increasing early growth may increase WUE and yield through an early increase in LAI. Anderson (1992) working with wheat in Australia also found that nitrogen improved WUE.

2.4 Nitrogen use

Nitrogen uptake is dependent both on the demand by the crop and the soil N availability. Total dry matter accumulation and total N uptake increases with increasing rate of nitrogen (Wilson *et al.*, 1994). Response to soil available N is a function of both N uptake from the soil and utilization of N within the plant to produce grain (Dwyer *et al.*, 1993).

Variations in nitrogen availability affect growth and development of crops and may lead to changes in crop physiological conditions at flowering and in grain set. Nitrogen deficiency delays both vegetative and reproductive phenological development reduces leaf expansion rate and leaf area duration (Uhart and Andrade, 1995). Nitrogen deficiency also reduces radiation interception and radiation use efficiency and the effect on the total dry matter ratios at harvest are associated with crop growth rate reduction at flowering. Water stress and nitrogen deficiency reduce leaf chlorophyll content and light absorption and increase reflectance (Uhart and Andrade, 1995) and reduce grain number and yield (Barbieri *et al.*, 2000).

2.4.1 Nitrogen fixation

Even though 78% of the earth's atmosphere consists of elemental nitrogen, the demand for the fixed nitrogen exceeds its availability. The majority of crop plants depend on nitrate or ammonia for their nitrogen source. Legumes that form root nodules can reduce atmospheric nitrogen through symbiosis with rhizobia and hence grow better than cereals in soils low in nitrogen (Kumar Rao *et al.*, 1990). Nitrogen fixation in the field is strongly influenced by the prevailing environmental conditions (Giller, 2001). The main environmental factors include physical factors (temperature, moisture), chemical factors (acidity, aluminum) and nutrients deficiency (Giller, 2001).

Nitrogen is a major factor benefiting cereals following legumes compared with cereals following non-legumes (Chalk *et al.*, 1993). Beneficial effects of legumes on the yield of subsequent crops have been demonstrated (Armstrong *et al.*, 1997) when the legumes were incorporated as crop residue (Haynes, 1997). Many cropping experiments have shown increasing yields and N uptake by cereal grown after legumes than when grown after cereals (Strong *et al.*, 1986). Benefits of legumes in the range of 0.2-2.68 ton/ha increases in yield in cereals have been reported (Peoples and Herridge, 1990), though the benefits depended on the antecedent crop used (Chalk, 1998). For the residual effects to occur, it is expected that the amount of fixed N and /or returned by legumes to the soil should be greater than the amount of soil N removed in the harvested grains (Haynes, 1993).

In addition to N fixation, legumes can increase N availability to companion cereal crop or subsequent crop (Kumar Rao, 1990) through litterfall decomposition. A medium duration pigeonpea grown as a sole crop had a large residual effect on the following maize crop. Grain yield and biomass increased by 57% and 32% respectively compared to a fallow treatment (Kumar Rao *et al*, 1983). It was estimated that pigeonpea had a beneficial effect on maize equivalent to about 40 kg N ha^{-1} which was partially attributed to a contribution of N from pigeonpea leaf fall. Sheldrake and Narayagan (1979) showed a substantial amount of nitrogen (32 to 36 kg N /ha) was present in leaf fall. The amount of N in the leaves that fall during growth of long duration pigeonpea may be as much as 68-84 kg N /ha (Kumar Rao *et al.*, 1996). Yield of sorghum were consistently higher following a sorghum/pigeonpea intercrop, and the N content in the soil had been increased significantly where pigeonpea had been grown (Rego and Rao, 2000).

2.4.2 Quantification of nitrogen fixation by pigeonpea

It is difficult to measure the amount of nitrogen fixed by pigeonpea in the field because it is deep-rooted and grows a long time. However the nitrogen fixed by pigeonpea of different maturity groups; medium and long duration in various cropping systems, needs to be quantified. Possible methods include nitrogen balance (difference method), acetylene reduction assay (ARA), ^{15}N isotope dilution and ureides in the xylem sap (Kumar Rao, 1990).

Nitrogen difference method is the simplest method and it involves measuring the uptake of N in the N fixing plant and in the non-fixing plant (reference crop) grown in the same soil. Subtraction of the N in the non-fixing plant will then give an estimate N fixation (Giller and Wilson, 2001). The method has an advantage of giving a measure of the total amount of N fixed over the length of the experiment. The advantage of this method is that N fixation is integrated over time and hence takes care of the environmental variables which influences N uptake by pigeonpea and the reference crop. The assumptions made in the N difference method are that the fixing crop and the reference crop exploit the same soil volume (have access to the same N pool) and take up the same amount of soil N. The method may either under or over estimate amount of N fixed if the reference crop and the fixing crop have different rooting characteristics and phenlogical duration, which would lead to differences in N uptake. Hence a suitable reference crop should have similar rooting patterns and phenological development as the fixing crop. Estimates of fixed N by pigeonpea genotypes of different maturity using sorghum as a non-fixing crop, ranged from 6-69 N kg/ha (Kumar Rao and Dart, 1987). Long duration cultivars apparently fix about 52% of total nitrogen uptake; although this would be expected to vary depending on several environmental conditions like rainfall, soil pH, temperature and diseases (Kumar Rao, 1990).

2.5 Resource use in intercropping systems

Intercropping system of cereals with pigeonpea has a number of advantages; e.g., producing higher yields per unit area through better use of natural resources, minimizing the incidence of insect pests, diseases and weeds and improving the nitrogen economy in legume associations. It also offers greater stability in production, meets domestic needs of the farmer and provide an equitable distribution of farm resources (Ali, 1990). Intercropping plants of differing maturities and/or canopy height reduces weed growth, lowers soil diurnal temperatures, controls erosion and maximizes growth resources (Zuofa *et al.*, 1992). Plant height, dry weight and total N content in sorghum grown intercropped with nodulated leucaena increased significantly compared to sole sorghum (Avery and Rhodes, 1990). Pigeonpea can also increase the available P pool of cropping systems in which it is grown by accessing Fe-P to a greater extent than other crop species can (Arihara *et al.*, 1991). However, in terms of yields, maize-pigeonpea intercropping system produced 24% higher than continuous sole maize (Rao and Mathuva, 2000). The annual grain legume-based cropping systems were 32-49 % more profitable than continuous sole maize, making them attractive to small farmers in semi-arid tropics (Rao and Mathuva, 2000). Grain yield of maize were higher when intercropped with legumes than as sole crops in absence of external inputs (Arihara *et al.*, 1991). There is need therefore, to determine the residual effect of pigeonpea on subsequent maize crop.

2.6 Methods of measuring productivity in the intercrop system

In any intercropping system the farmer is interested in the land use efficiency (Adhiambo, 1996). A number of methods are used to compare advantage of intercropping over sole cropping. The most common method used is land equivalent ratio (LER). LER is defined as (Mead, 1986);

$$LER = \frac{Yield\ of\ 'a'\ in\ intercrop}{Yield\ of\ 'a'\ in\ sole\ crop} + \frac{Yield\ of\ 'b'\ in\ intercrop}{Yield\ of\ 'b'\ in\ sole\ crop} \qquad \textbf{Equation 5}$$

A value of LER greater than one indicates an overall biological advantage of intercropping.

Yield advantages from intercropping as compared to the sole cropping are often attributed to mutual complimentarity effects and minimizing the intercrop competition of component crops on available resources like light, water and nitrogen. This could be due to spatial and temporal separation due to differences in plant architecture (canopy height and rooting characteristics), peak nutrient demand and moisture uptake at different times. The thesis quantifies resource use (light, water and nitrogen) patterns in maize - pigeonpea intercrop system through experiments described in chapter 3.

CHAPTER 3

MATERIALS AND METHODS

3.1 Greenhouse experiment

An experiment was carried out in the greenhouse to identify a suitable reference crop to determine the amount of N fixed by pigeonpea. Maize (Hybrid 511 and Katumani composite), sorghum (MB30 and IS 25545) and cotton (Hart 89 M and Uka 59/146) were evaluated as the reference crops.

Top 20 cm soil was collected from the field, dried at 105°C to determine the moisture content. Bulk density (ρ) was also determined using the equation below as in (Okalebo *et al.*, 2002);

$$Bulk\ density\ (g\ cm^{-3}) = \frac{Mass\ of dried\ soil\ (g) - Mass\ of\ metal\ tube\ (g)}{Volume\ of\ metal\ tube\ (cm^{-3})}$$ **Equation 6**

Polythene sleeves (30 cm in diameter and 100 cm long) were sealed at the bottom, and perforated on the sides to allow air penetration and prevent water logging and filled with soil and placed on a wooden framework for support (Plate 1). Two plants were planted in each polythene tube to ensure unrestricted root growth. The experimental design was completely randomized design replicated five times. The treatment included; one medium duration pigeonpea (ICEAP 00557), two long duration pigeonpea (erect-ICEAP 00053 and semi-erect- ICEAP 00040), two maize varieties (Hybrid 511 and Katumani), two varieties of sorghum (MB30 and IS 25545) and two cotton varieties (Hart 89 M and Uka 59/146).

Plate 1. Crops grown in polythene sleeves in the greenhouse.

3.1.1 Crop phenological development

Crop growth was determined by harvesting the crops at 120 DAP. The plants were later oven dried at 70°C (to constant weight) to determine dry mass, and ground for total N determination.

3.1.2 Rooting characteristics

Root samples were taken at 120 DAP. The tubes were cut into segments of 30-cm long segments i.e. (0-30, 30-60 and 60-90 cm). Each segment was submerged in water in a plastic container and the soil-root-water mixture was stirred by hand to break the soil clods to loose the roots. The roots were collected by decanting through a 200-μm sieve and manually collected with forceps. The living roots (white) were picked and put into bottles containing clean water and were later stored in the refrigerator at 5°C awaiting root length determination (Tennant, 1975). The roots were stained red with 1% fuschin dye (for easy counting). Graph paper, ruled in centimeters was placed under the transparency paper. The wet roots were then placed on to the transparency paper, and they were positioned randomly over the transparency with forceps to avoid overlapping. Counts of the intersections of the roots with the vertical and horizontal graph lines were made using a hand tally counter to facilitate the counting procedure. Root length was determined using the equation below (Tennant 1975);

$$R = {}^{11}\!/_{14}\, N \times g \qquad \textbf{Equation 7}$$

Where R is the Root length, N is the number of intersections, g is the grid unit. The roots were later dried in an oven at 105°C for about 24 hours for dry mass determination.

3.2 Field experiment

3.2.1 Site description

A field experiment was carried out at Jomo Kenyatta University of Agriculture and Technology (JKUAT), Thika. The site have the following characteristics: rainfall 768 mm p.a., altitude 1549 m above sea level, average evaporation 105 mm p.a., maximum temperatures of 24.1°C and minimum temperature of 13.5°C. The soil type is a eutric cambisol with dark brown colour on all the horizons. Texture is sandy clay and gravel sandy clay, with 37% (0-8 cm) clay in the top horizon and 41% (25-50 cm) in the lower horizon. Structure was weak, fine, course and sub angular blocky. Consistence was hard when dry, friable when moist and slightly sticky when wet. The soil is well drained with a land slope of 0-2%.

Table 1. Soil chemical characteristics at JKUAT, Thika.

Chemical		Depth (cm)	
characteristics	0-8 cm	8-25 cm	25-50 cm
pH	6.7	6.5	7.1
C %	1.14	1.24	1.18
N %	0.04	0.06	0.04
C/N	9	9	9.2
Calcium	6.55	7.1	8.4
Potassium	0.6	0.4	0.7
Magnesium	2.0	1.83	2.08
CEC	10	10.3	11.0
Sodium	0.2	0.15	0.25

The experiment was laid out as a randomized complete block design (RCBD) replicated four times with seven cropping patterns comprised of; two pigeonpeas maturity types - 2 long duration (erect-ICEAP 00053 and semi-erect-ICEAP 00040) and one medium duration (ICEAP 00557). type intercropped with maize (Katumani composite) with sole of the same crop as a check. Other sole crops included two varieties of cotton (Hart 89 M and Uka 59/146) and one variety of sorghum (MB30) as the reference crops.

The intercrop planting arrangement was three rows of maize interspersed with two rows of pigeonpea (75 cm by 20 cm). Farmers accept this planting arrangement because it does not reduce maize yields, which is considered to be the main crop (ICRISAT, 1995). The intercrop plots were 10 m long by 4 m wide and the monocrop plots were 10 m long by 3 m. The plant population of maize was 44289 and 26700 plants/ha while pigeonpea was 66633 and 26500 plants/ha in the sole and intercrop plots respectively. Cotton spacing was 100 cm by 100cm while for sorghum was (75 cm by 20 cm). The experiment was sown in the short rains on 30th October 2001 and a second maize season was sown in the same plots on 28th February 2002. The residual effect experiment was sown on 18th October 2002 to check the residual nutrient effects of the pigeonpeas on maize yield.

The plots were kept free from weeds manually while pod borers in pigeonpea were controlled using chemicals (Dimethoate and Karate). The fertilizers applied were triple supper phosphate (TSP: 46 % P_2O_5) at 13 kg P/ha at planting and calcium ammonium nitrogen (CAN: 26 % N) at 12 kg N/ha during vegetative phase in two maize seasons.

3.2.2 Crop growth and phenological development

The time to emergence, flowering and maturity stage were recorded.

Crop height was obtained by measuring an individual plant using a meter rule (cm) from the base to the top every 14 days.

3.2.2.1 Crop total dry matter.

Crop growth was determined by sequentially harvesting pigeonpea and maize after every 14 days. Four plants of pigeonpeas and maize were sampled from each plot, ensuring the subsequent sample was taken far from the gap. Final samples for yield determination were taken from the three center rows. At each harvest, plants were cut at the ground level, fresh weight recorded of the three rows, two plants selected and the fresh weight taken. The two plants were put into plastic bags and stripped into various components, namely: - leaves, stems, cobs/pods and seeds (depending on the crop phenological stage) to determine the dry matter production and partitioning patterns. The plant components were later oven dried at 70°C (to constant weight) to determine dry mass, and ground for total N determination.

3.2.2.2 Leaf area index

Leaf area was determined at vegetative stage on ICEAP 00053 and podding stage for ICEAP 00040 and ICEAP 00557. Leaf area was determined by selecting 40 fully expanded green leaflets from 2 plants and punching 80 disks with a cork borer of 1 cm internal diameter. The disks were oven dried at 70°C for 48 hours. The equation was used to determine leaf area was as follows (Mburu, 1996);

$$LA_{total} = Lwt_{total} \times \left({}^{LAdisc}\!/_{Lwtdisc} \right) \qquad \textbf{Equation 8}$$

LA discs and LA $_{total}$ are the leaf disc and total leaf area respectively (cm^2).

Lwt disks and Lwt total are the weights of the leaf discs and the total plant leaf weight respectively (g).

3.2.2.3 Fractional solar radiation interception

Radiation interception of photosynthetically active radiation was measured in both the sole crop, and the intercrop using a sunfleck ceptometer (SF-80 Decagon, Pullman, Washington). Ten measurements were taken below the canopy by holding the ceptometer perpendicular to the rows throughout the growing period and two measurements above the canopy per plot. The measurements were taken at 11.30 am to 1.30 pm. (local time) after every 14 days. The PAR intercepted was calculated by subtracting the ceptometer reading below the canopy from the ceptometer reading above the canopy.

$$\%PAR\ intercepted = \frac{(PAR_a - PAR_b)}{PAR_a} \times 100$$ **Equation 9**

Where PAR_a = PAR above the canopy

PAR_b = PAR below the canopy

3.2.3 Soil water content changes

Soil profile water content changes were determined using a neutron probe (Dicot, Abingdon, UK. Aluminum access tubes (120 cm long with an internal diameter 50 mm) sealed at the lower end installed in auger-bored holes, that were slightly smaller than the tubes. Three-access tubes (between maize rows, maize and pigeonpea row and pigeonpeas rows) were installed per plot in the intercrops prior to sowing. Only one access tube per plot was installed in the sole crop treatments. Neutron counts were taken over 16 seconds 20 cm intervals starting at 50 cm depth up to 110-cm after every 14 days. Soil water content changes in the top 30 cm was determined using gravimetric method. Neutron count in water was made after field measurements for the purpose of calibration. Calibrations in the field were made by auguring 3 holes, 20 cm from the access tube at 10 cm interval to a depth of 100 cm at different soil moisture content. Soil bulk density (g cm $^{-3}$) was determined to convert gravimetric water to volumetric basis.

Table 2. Soil bulk density at depths 0-10, 10-30. 30-50, 50-70 and 70-90 at JKUAT, Thika.

Depth (cm)	Bulk density (g/cm^3)
0-10 cm	1.67
10-30 cm	1.71
30-50 cm	1.66
50-70 cm	1.79
70-90 cm	1.68

3.2.4 Digestion of plant material for total N analysis

Ground oven dried (70°C) plant or soil samples were weighed into 0.3 g digestion tubes and mixed with of salicylic acid, hydrogen peroxide, concentrated sulphuric acid and selenium powder. The tubes were put into a digestion block and heated to 110 °C for 1 hour and cooled by adding hydrogen peroxide. Temperature was later raised to 330 °C for the solution to turn colourless. The tubes were removed from the digestion block and allowed to cool to room temperature. Twenty-five ml of distilled water was added and mixed well until no more sediment dissolved. The tubes were allowed to cool and the content made up to 50 ml with distilled water. The tubes were allowed to settle and a clear solution was taken from the top of the tube for analysis. Total N was later determined using steam distillation as described by (Okalebo *et al.*, 2002).

3.2.4.1 Steam distillation for total N determination

The steam distillation apparatus (Markham N still) was set up and steam passed through for 30 minutes. A steam blank (50 ml) distillate was collected and titrated with N/70 or M/140 HCl for plants and soils respectively. Aliquot measures of 5 ml from the digest (section above) was taken for distillation and the distillate collected in a solution containing 6.5 ml 0.01 N NaOH and 5 ml 1% boric acid-indicator solution. The distillate was titrated with N/140 HCl to a grey end-point using a microburette. Total N was calculated as:

$$\frac{(a-b) \times 0.2v \times 100}{1000 \times w \times al} \qquad \textbf{Equation 10}$$

$$\frac{(a-b) \times 0.1v \times 100}{1000 \times w \times al} \qquad \textbf{Equation 11}$$

Where; a = volume of the titre HCl for the blank

b = volume of the titre HCl for the sample

v = final volume of the digestion

w = weight of the sample taken and

al = aliquot of the solution taken for analysis.

3.2.4.2 Estimation of the amount of nitrogen fixed by pigeonpea using the difference method

Nitrogen fixation was determined using the nitrogen difference method (Giller and Wilson, 2001). The N derived from fixation (Ndfa) is calculated as the difference between total N in the pigeonpea crop and total N in the non-fixing crops. Cotton (Hart 89 M and Uka 59/146) was used as the reference crop.

3.2.4.3 Litter fall collection

Litter fall was determined by putting 1 m^2 wire mesh below the pigeonpea canopy in both the sole and the intercrop to collect the falling leaves. Litter fall was collected after every 14 days and later oven dried at 70°C (to constant weight) to determine dry mass, and ground for total N determination (Okalebo *et al.*, 2002).

3.2.4.4 Soil available N and total tissue N

Soil samples were taken to determine the soil mineral N and total N distribution in the profile site. Samples were taken one week before planting, at the middle and at the end of the crop-growing season. The soil samples per plot were collected at 0-20, 20-50, and 50-100 cm and two samples per plot were bulked. The soil samples for total N were air dried, ground manually with a pestle and mortar and passed through 2-mm sieve. A soil sample (0-20 g) was taken and digested and analyzed for total N using micro Kjeldhal method (Okalebo *et al.*, 2002).

3.2.4.5 Soil mineral N determination

Soil samples were collected at 0-20, 20-50, and 50-100, depths using an auger at the beginning, middle and end of the season. Two soil profiles per plot were sampled and the soils were thoroughly mixed. Soils were stored in iceboxes for transportation and later in a deep freezer for mineral N determination. Thirty grams of the thawed soil was weighed into a 200 ml plastic container and 100 ml 2 M KCl added to the soil and put in a shaker for 1 hour. The contents were filtered. Another 20 g of the soil sample was dried in the oven at 105°C for soil moisture content determination. NO_3^--N and NH_4^+-N was determined by steam distillation of the KCL extract using 0.4 g Devarda's alloy and 0.2 g MgO as catalysts. The distillate was collected in H_3BO_3 solution and titrated with dilute H_2SO_4 for the N determination.

All the data was analyzed using GENSTAT (1995) and means were separated using LSD test at a significance level of 5 %.

CHAPTER 4

GREENHOUSE EXPERIMENT RESULTS AND DISCUSSION

4.1 Biomass accumulation

Maize and sorghum accumulated more aboveground dry matter (g/plant) compared to pigeonpea in both season 1 and 2 (Table 3, Appendix 1). Cotton Uka 59/146 was comparable to medium duration pigeonpea while Hart 89 M to long duration pigeonpeas in both seasons.

Table 3. Shoot and root dry mass of maize, sorghum, cotton and pigeonpea in the greenhouse at University of Nairobi, Kabete field station farm.

Crop	Variety	-----Shoot dry mass (g/plant)----	
		Season 1	Season 2
Pigeonpea	MD	3.06	7.20
	LDE	10.08	11.54
	LDSE	12.18	13.08
Maize	MZ	18.25	17.47
	H511	23.52	21.63
Sorghum	IS25545	17.43	20.57
	MB30	21.82	20.13
Cotton	Hart 89 M	10.83	9.48
	Uka 59/146	5.62	6.67
SED		3.4	2.706

MZ = Katumani maize, H511 = Hybrid 511, MD = medium duration, LDSE = long duration semi-erect and LDE = long duration erect pigeonpea. SED is the standard error of difference.

4.2 Root length density and dry mass

The root length density within each crop species was similar but different among different crops (Figure 1, Appendix 1). The root length densities of sorghum and maize were similar but higher than of pigeonpea and cotton. Root length densities in all the crops decreased with depth and at least 50 % of the roots were in the top 30-cm. The total root length density in the top 30-cm were 405, 372, 165, 179 and 136 cm cm^{-3} for sorghum. maize, cotton, long duration semi-erect and medium duration pigeonpea respectively (Figure 1). However there was no significant difference between cotton and pigeonpea root length density.

Root dry mass of sorghum and maize was similar and higher than that of cotton and pigeonpea in both seasons (Figure 2). Total root dry mass for pigeonpea ranged between 0.7-1.5 (g/plant), and of cotton, sorghum and maize ranged between 0.7-1.1, 2.7-3.9 and 3.9-4.4 (g/plant) respectively. Although sorghum had a higher root length density than maize, maize had higher root dry mass because sorghum had finer roots than maize.

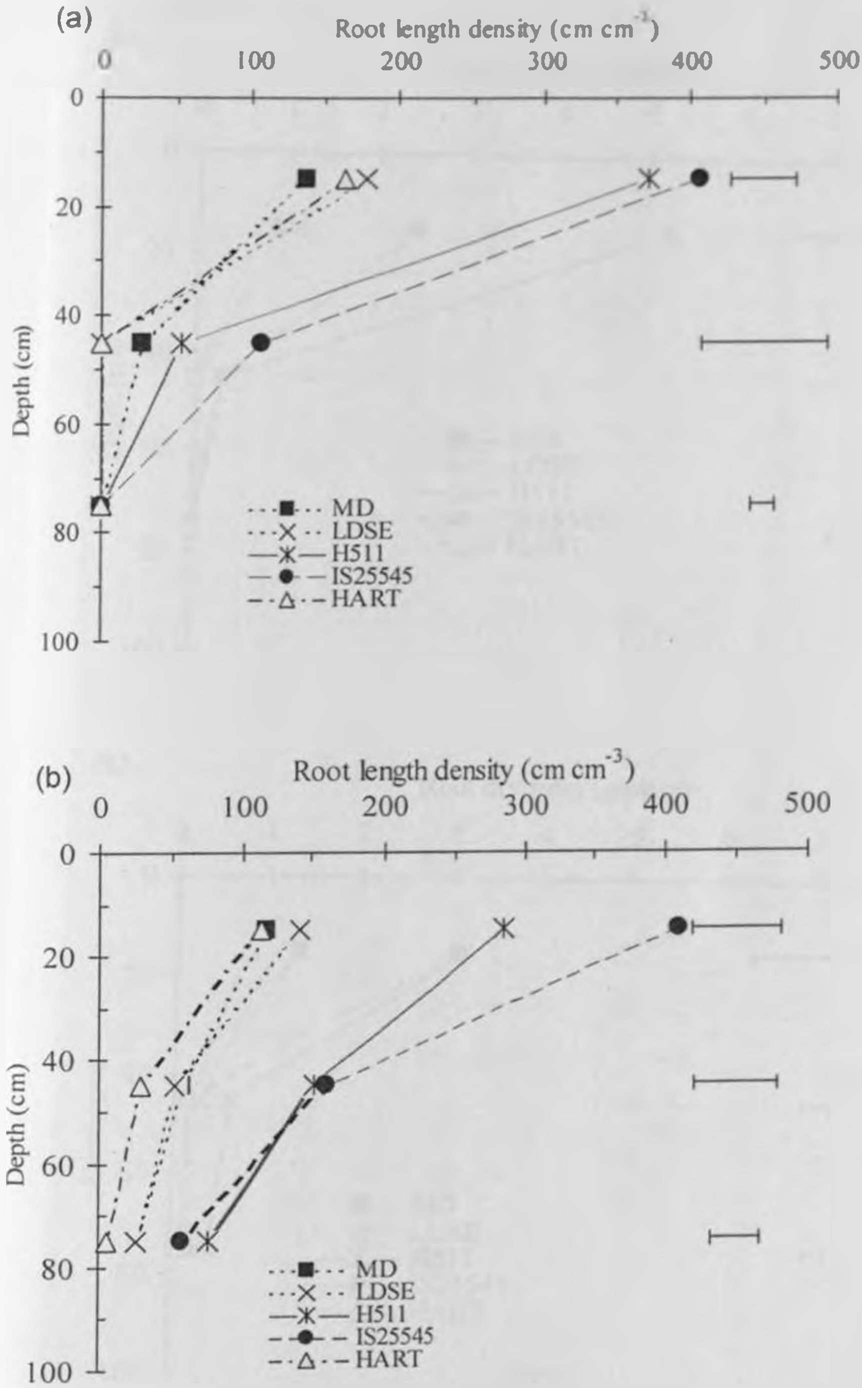
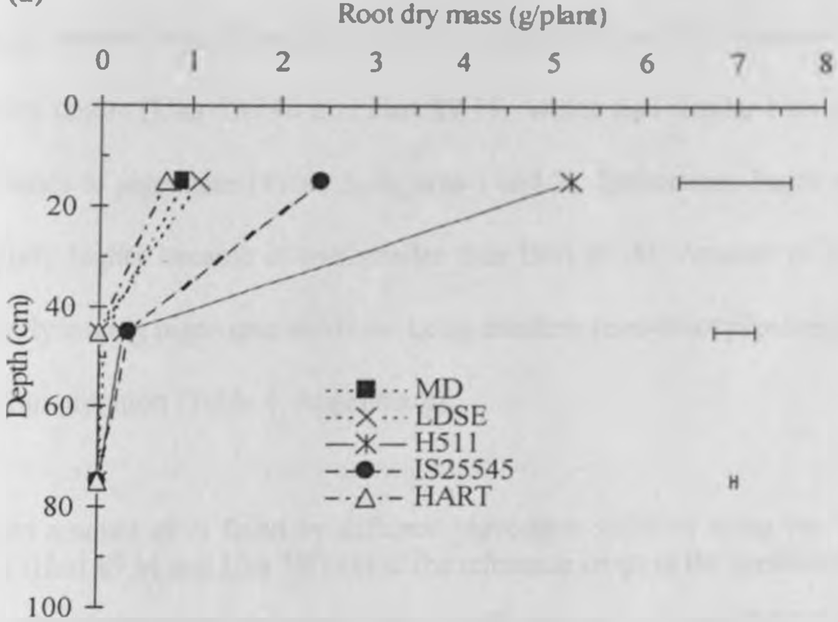


Figure 1. Root length density (cm cm^{-3}) of maize (H511), sorghum (IS25545), cotton (Hart) and pigeonpea (MD- medium duration and LDSE - long duration semi-erect) at 0-30 cm, 30-60 cm and 60-90 cm in the greenhouse (a) season 1 and (b) season 2, respectively. Bars represent least significant difference values (P=0.05).

(a)



(b)

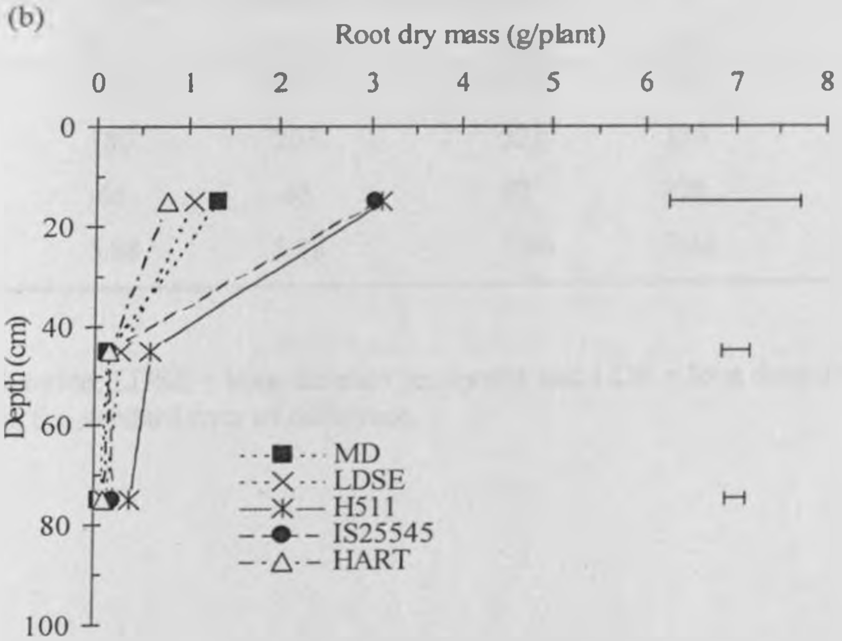


Figure 2. Root dry mass (g/plant) of maize (H511), sorghum (IS25545), cotton (Hart) and pigeonpea (MD- medium duration and LDSE - long duration semi-erect) at 0-30 cm, 30-60 cm and 60-90 cm in the greenhouse (a) season 1 and (b) season 2, respectively. Bars represent least significant difference values (p=0.05).

4.3 Nitrogen derived from atmospheric fixation

Sorghum and maize accumulated higher biomass than pigeonpea; therefore estimation of N fixed was based on cotton (Uka 59/146 and Hart 89 M), which had similar biomass and rooting characteristics to pigeonpea (Table 3, Figures 1 and 2). Estimations based on Uka 59/146 were slightly higher because it was smaller than Hart 89 M. Amount of N fixed differed significantly among pigeonpea cultivars. Long duration semi-erect pigeonpea fixed more N than medium duration (Table 4, Appendix 2).

Table 4. Estimated amount of N fixed by different pigeonpea varieties using two cotton varieties (Hart 89 M and Uka 59/146) as the reference crops in the greenhouse.

Pigeonpea varieties	------Season 1---------		------Season 2-------	
	---------------------N Fixed (mg/plant)-------------------			
	Hart	Uka	Hart	Uka
LDSE	188	211	312	356
LDE	180	203	321	336
MD	-66	-43	82	126
SED	5.88	5.88	7.06	7.92

MD = medium duration, LDSE = long duration semi-erect and LDE = long duration erect pigeonpea. SED is the standard error of difference.

4.4 Discussion

Similarities between cotton and pigeonpea rooting characteristics and biomass accumulation suggest that cotton was the appropriate reference crop to estimate amount of N fixed by pigeonpea. In contrast, maize and sorghum had high biomass accumulation, root length density and root dry mass; therefore N fixation was based on cotton. Use of non-fixing reference crops corresponding to each pigeonpea maturity improves accuracy of estimating the N fixed (Mapfupo *et al.*, 1999).

Root length density and the root dry mass decreased progressively with depth and at least more than 50 % of the roots were located at the top 30 cm. Similar observations were made by Mburu (1996) that approximately 80% of the total root system of beans was found within the top 45 cm. Similarities in the root morphology of cotton and pigeonpea may have been due to tap root system while maize and sorghum have fibrous rooting system The average values of root length density of sorghum at the soil depth of 0-60 cm were consistently higher than those of pigeonpea (Katayama, *et al.*, 2000). The higher roots dry mass for maize than sorghum could be attributed to maize having thicker and few roots while sorghum had fine and many roots.

Long duration cultivars fixed more N than the medium duration pigeonpea probably attributable to high biomass production, which resulted in high amount of N by the long duration pigeonpeas. These results corroborate findings of (Kumar Rao, 1990) that long duration varieties fix more N than early maturity groups.

CHAPTER 5

FIELD EXPERIMENT RESULTS AND DISCUSSION

5.1 Experimental site characteristics during the period of the study

The total rainfall received during the period of the study was 768 mm; with the highest rainfall at 130 to 200 days after planting (DAP) in the month of March, April and May 2002 (Figure 3a). Rainfall amount in the first maize season was lower (149 mm) than the second maize season (619 mm). However irrigation (200 mm) was done to supplement low rainfall received in the first maize season. Mean temperatures were 24.1°C and 13.5°C for maximum and minimum temperature respectively (Figure 3b).

5.2. Crop phenological development

Emergence differed with crop type (Table 5). Emergence of pigeonpea occurred one day later after the emergence of maize. The average final percentage of emergence was 90%, 60%, 50% and 5% for maize, long duration semi-erect, medium duration and long duration erect respectively. Long duration semi-erect pigeonpea achieved the best final stand compared to the medium duration and long duration erect pigeonpea. Long duration erect was replanted one month later due to the poor germination.

Tasseling of maize occurred at 60 DAP and physiological maturity was from 90 days, while harvesting was done at 112 DAP. There were differences in duration to flowering and physiological maturity among pigeonpea cultivars. The medium duration attained 50% flowering 20 days and reached its physiological maturity 30 days earlier than the long duration semi-erect (Table 5). Long duration semi-erect attained 50% flowering and attained its physiological maturity 50 days earlier than the long duration erect. Intercropping had no effect on the duration to 50 % flowering and time to physiological maturity.

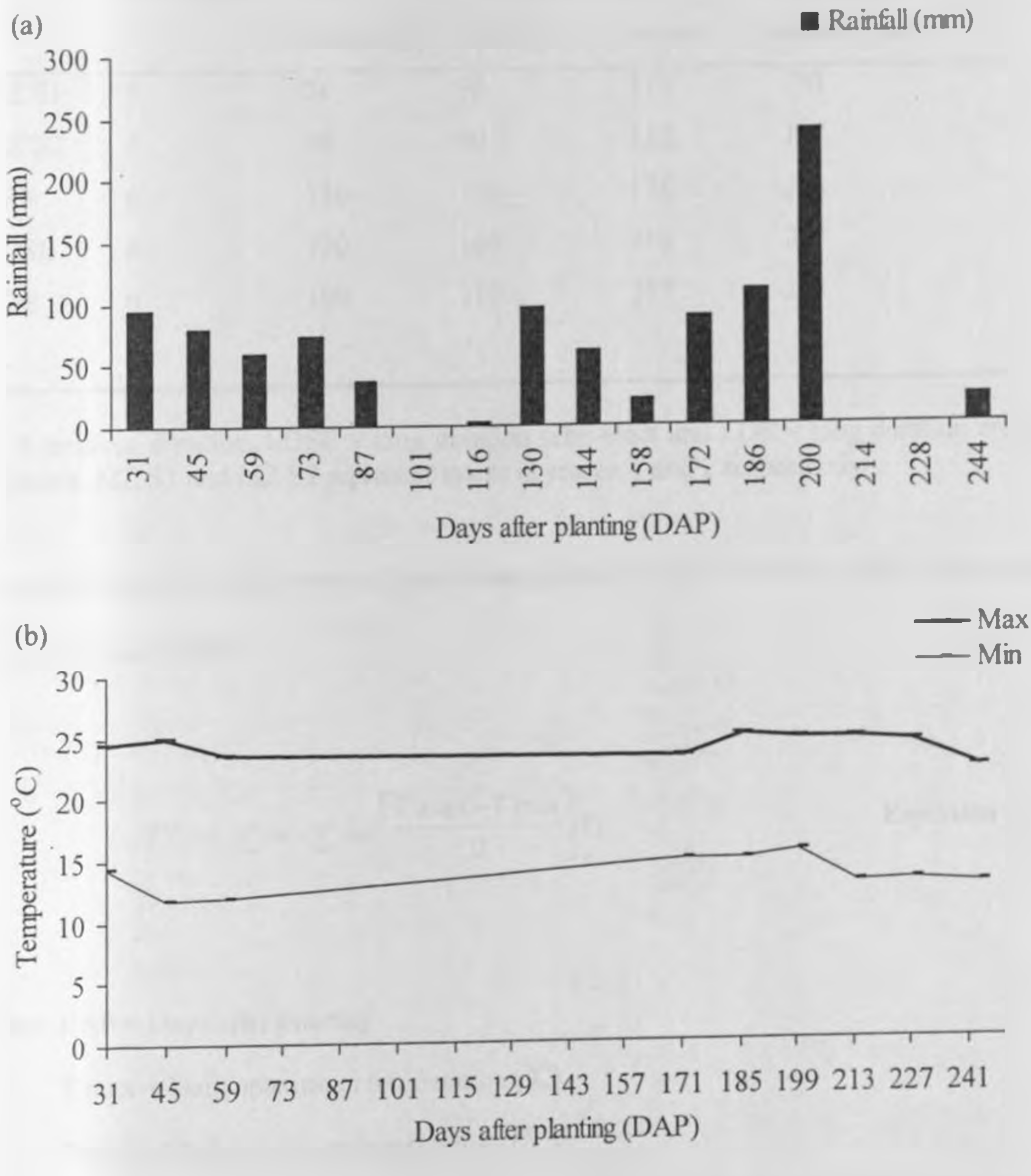


Figure 3. (a) Bi weekly rainfall and irrigation water (mm) and (b) diurnal minimum and maximum temperature (°C) amount from October, 2001 to June, 2002 at JKUAT, Thika.

Table 5. Crop phenological stages of maize and three varieties of pigeonpea at JKUAT, Thika.

Crop	Phenological durations (days)				
	Emergence	50% Flowering	Physiological Maturity	Final harvest	Plant height at maturity (cm)
MZ S1	5	56	90	112	103
MZ S2	5	60	90	112	107
MD	6	110	130	175	228
LDSE	6	130	160	210	257
LDE	6	190	210	257	243

MD = medium duration, LDSE = long duration semi-erect and LDE = long duration erect pigeonpea. MZ S1 and MZ S2 represent maize in season 1 and 2 respectively.

Crop phenological duration was calculated using maximum and minimum daily temperatures (TT_{DAP}) (Squire 1990);

$$TT_{DAP} = \sum_{0}^{n} DAP = \sum_{0} DAP \left[\frac{T\max - T\min}{2} \right] T_b$$ **Equation 12**

Where: DAP = Days after planting

T max = Daily maximum temperature (°C)

T min = Daily minimum temperature (°C)

T_b = Base temperature (°C) and which was assumed to be 12.8 (Reddy, 1990) for all the phenological stages.

Long duration erect had a longer vegetative stage but had a shorter reproductive stage compared to the medium and long duration semi-erect probably because the former grew during the cooler season while the later grew during the warmer season (Table 6).

Table 6. Relationship between crop phenology stages and thermal time (° C days) since zero days after planting at JKUAT Thika.

Crop	----------------Phenological duration (° C days)---------------------------			
	Emergence	Flowering	Physiological maturity	Final harvest
MZ S1	38	337	559	713
MZ S2	35	388	586	698
MD	44	727	871	1177
LDSE	44	871	1087	1413
LDE	44	1272	1413	1672

MD = medium duration, LDSE = long duration semi-erect and LDE = long duration erect pigeonpea. MZ S1 and MZ S2 represent maize in season 1 and 2 respectively.

5.2.1 Crop height

Crop height increased with time in both sole and intercropped maize and pigeonpea (Figure 4). During vegetative phase there was a drastic increase in crop height but the increase slowed down towards the maturity stage. Maize was taller in the second season than in the first season both in the intercrop and in the sole crop system. Intercropping had no effect on maize plant height in both seasons except maize intercropped with long duration erect at the end second maize season (Appendix 3).

Maize was taller than either sole or intercropped pigeonpea at the beginning of the season (0-115 DAP) but in the second season (115-220 DAP), long duration pigeonpea types were taller while the medium duration pigeonpea was shorter than maize.

Increase in crop height depended on the pigeonpea duration type (Figure 4, Appendix 4). The maximum height attained by different pigeonpea maturity types was 245, 263 and 145 cm at 220 DAP for the long duration semi-erect (LDSE), long duration erect (LDE) and medium duration (MD) pigeonpea respectively. Long duration semi-erect was taller than the long duration erect and the medium duration pigeonpea early in the season (0-115 DAP); but towards the end of the season, long duration erect was the tallest (Plate 2). Intercropped pigeonpeas attained similar plant heights as in the sole pigeonpea at the end of the season (220 DAP). In the intercrops, the maximum height of pigeonpeas was 246 cm, 231 cm and 131 cm at 220 DAP for the intercropped long duration erect, long duration semi-erect and medium duration pigeonpea respectively.

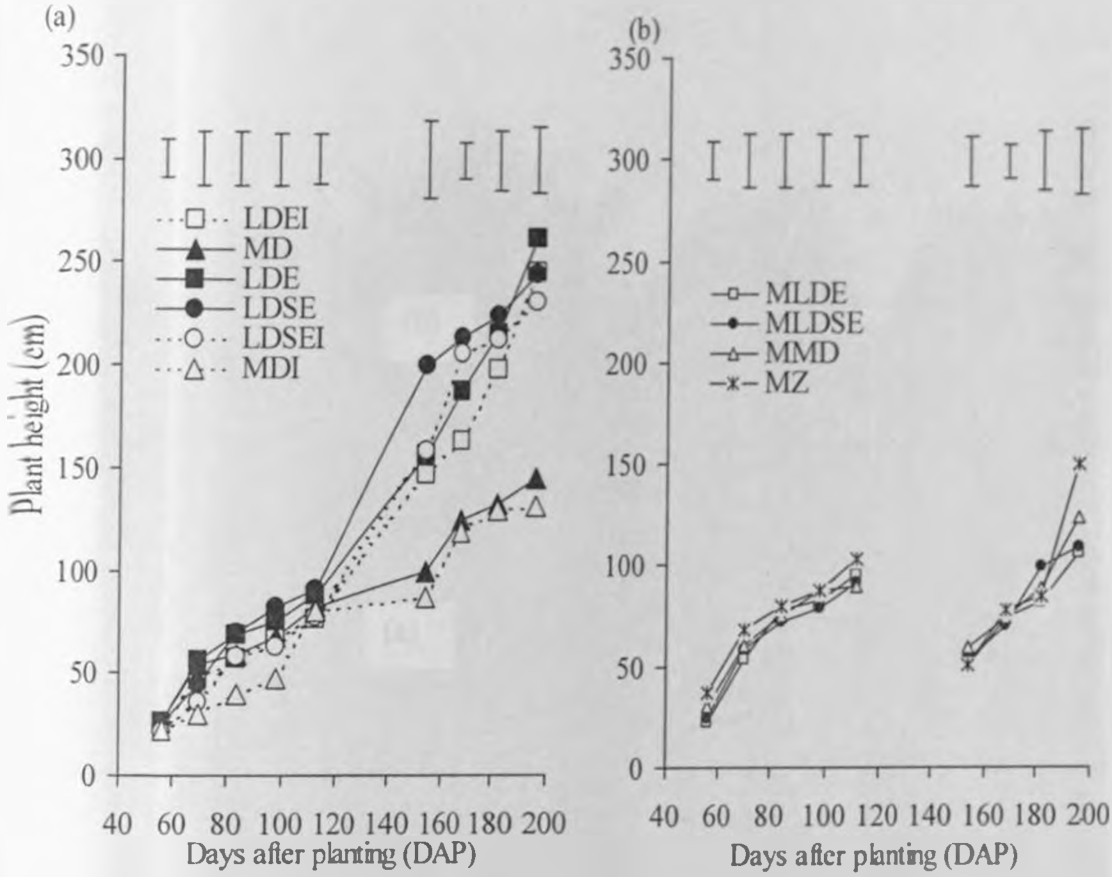


Figure 4. Change in plant height (cm) with time for pigeonpea (a) and maize (b) in the sole and intercrop at JKUAT, Thika. MD = medium duration, LDSE = long duration semi-erect and LDE = long duration erect pigeonpea. MZ = sole maize, whereas MLDSE, MLDE and MMD are maize intercropped with long duration semi-erect, long duration erect and medium duration pigeonpea respectively. Bars represent LSD values (P=0.05).

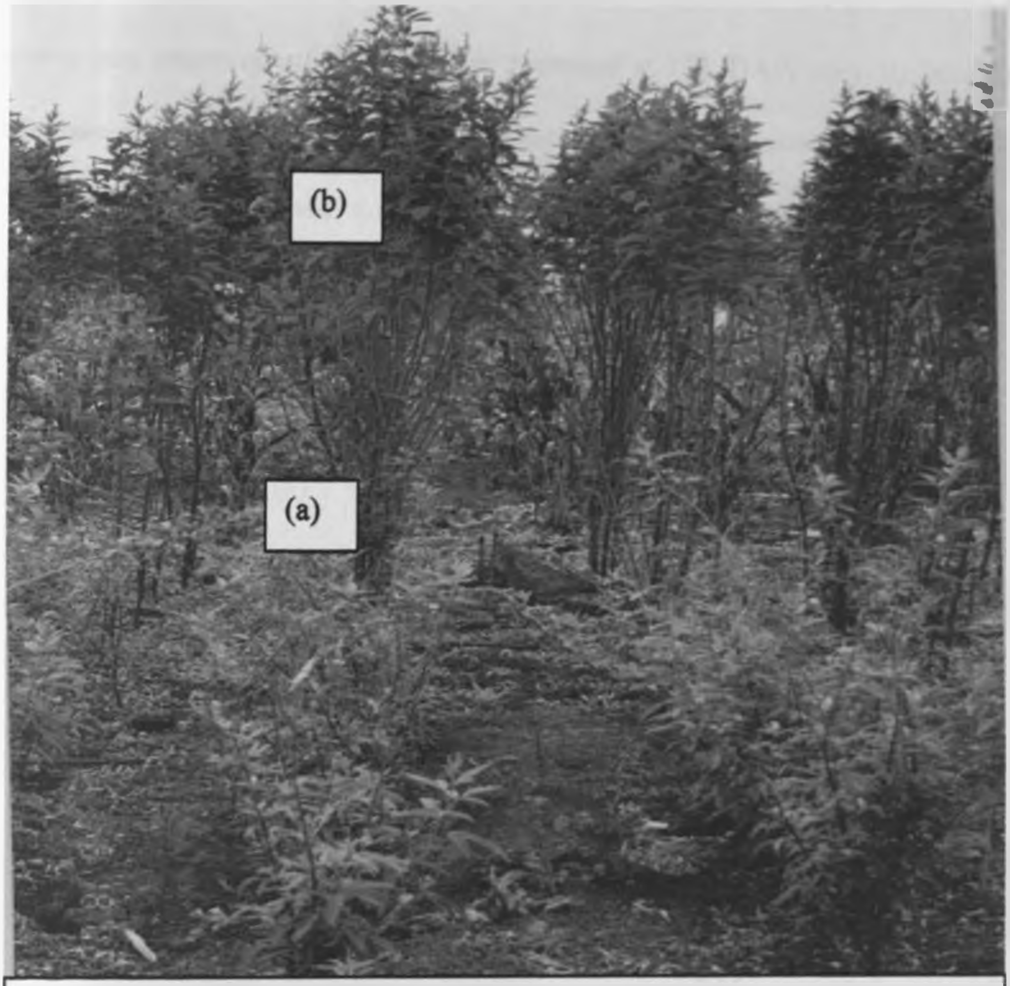


Plate 2. Pigeonpea varietal differences in crop height. (a) is medium duration and (b) is long duration pigeonpea.

5.2.2 Leaf area index

Leaf area index during the growing season differed among pigeonpea varieties (Figure 5, Appendix 5). Highest leaf area index in long duration semi-erect and the medium duration pigeonpea was observed at 120 DAP but decreased at 171 DAP, possibly because at the reproductive stage assimilates were remobilized into pods and seeds resulting in leaf fall. Leaf area index increased with time for the long duration erect, which was at its vegetative phase.

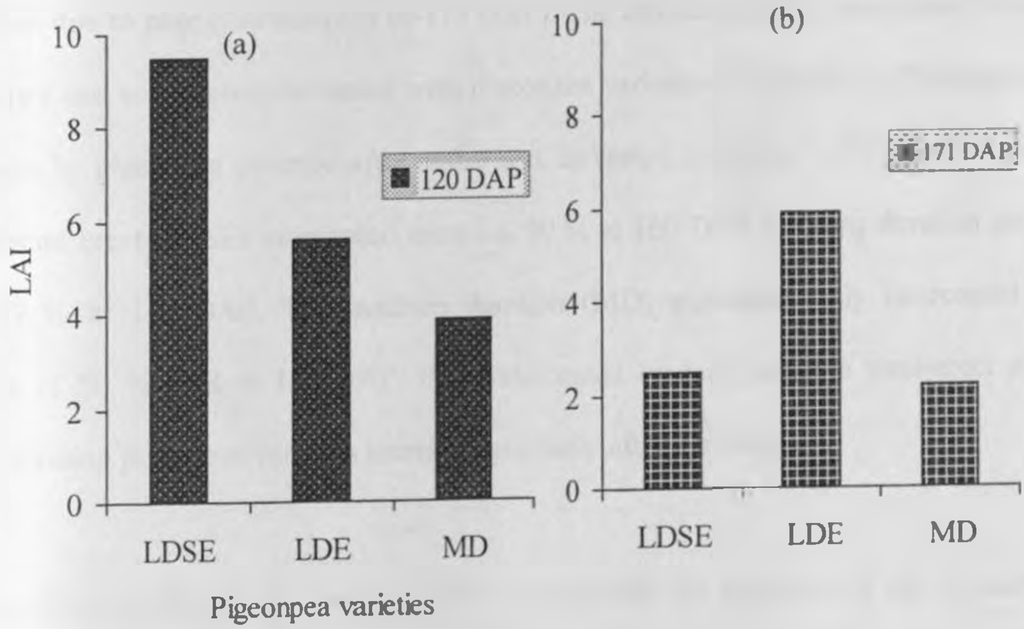


Figure 5. Leaf area index of three pigeonpea duration types at (a) 120 DAP and (b) 171 DAP. MD = medium duration, LDSE = long duration semi-erect and LDE = long duration erect pigeonpea. Bars represent LSD values (P=0.05).

5.2.3 Fractional photosynthetically active radiation (PAR) interception

The proportion PAR intercepted by both maize and pigeonpea increased over time and thereafter decreased as the crops matured (Figure 6). The maximum PAR intercepted by sole maize in season 1 and 2 was 43 % and 40 % respectively. Sole maize intercepted more light than either the sole or intercropped pigeonpea (0-70 DAP). Maize PAR interception decreased between 70 DAP (silking stage) and harvesting stage (115 DAP). The long duration semi-erect (LDSE) and medium duration (MD) pigeonpea in the sole and intercrop intercepted similar amounts of PAR while long duration erect (LDE) had the lowest interception due to poor establishment (0-115 DAP). The amount of PAR intercepted by the intercropped and sole pigeonpea varied with pigeonpea varieties (Appendix 6). The highest interception by pigeonpea occurred after maize was harvested in season 1 (115 DAP). Long duration semi erect (LDSE) intercepted more i.e. 90 % at 160 DAP and long duration erect (LDE) 89 % at 172 DAP. The medium duration (MD) pigeonpea only intercepted a maximum of 50 % PAR at 130 DAP. PAR intercepted by long duration semi-erect and medium duration pigeonpea varieties increased gradually after harvesting.

Light extinction coefficient (k) was determined by plotting the logarithm of the fractional PAR transmitted through the canopy against leaf area index. The k value was greater for the long duration semi erect (0.59) than long duration erect (0.47) and the medium duration (0.39) pigeonpea (Figure 7). This indicates that medium duration variety can be planted at higher planting density than long duration semi-erect and long duration erect.

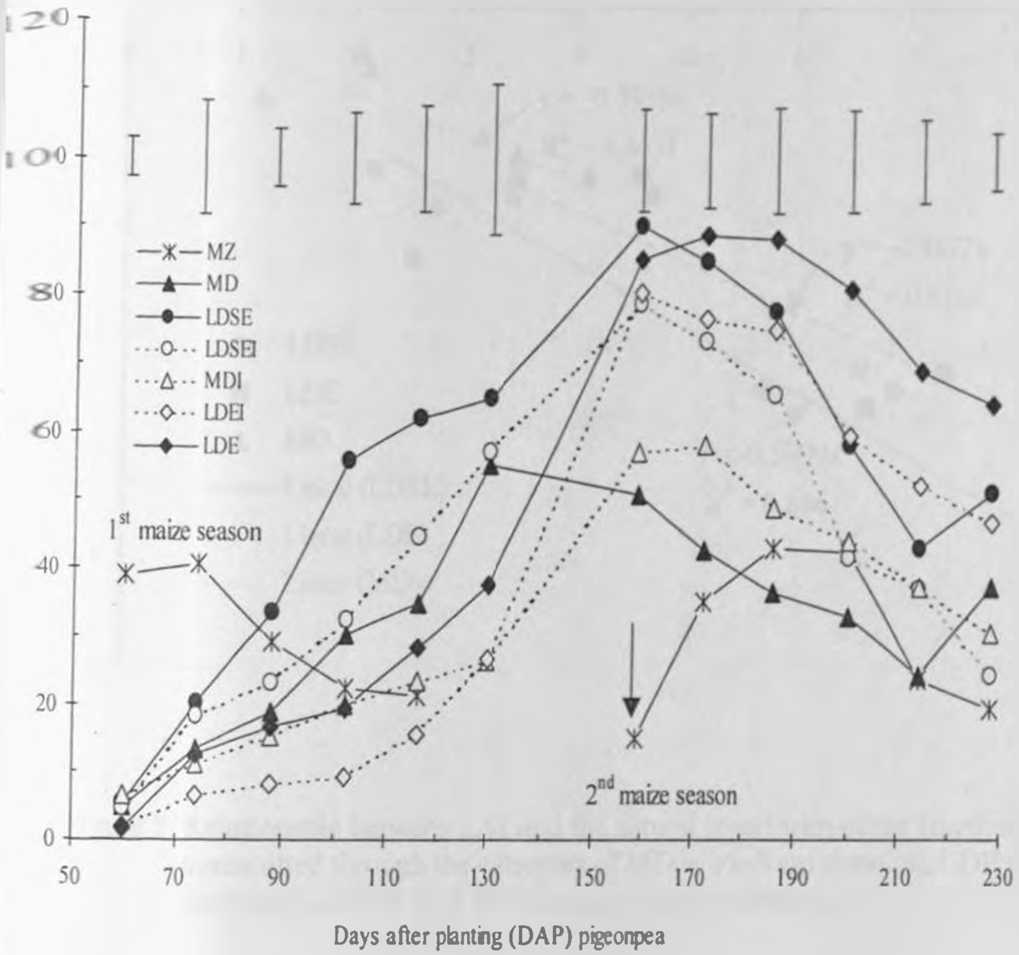


Figure 6. Fractional PAR light interception by sole crop and intercropped maize and pigeonpeas over time at JKUAT, Thika. MZ = maize, MD = medium duration, LDSE = long duration semi-erect and LDE = long duration erect pigeonpea. MDI, LDSEI and LDEI represent intercrop of medium duration, long duration semi-erect and long duration erect with maize. Bars represent LSD values (P=0.05).

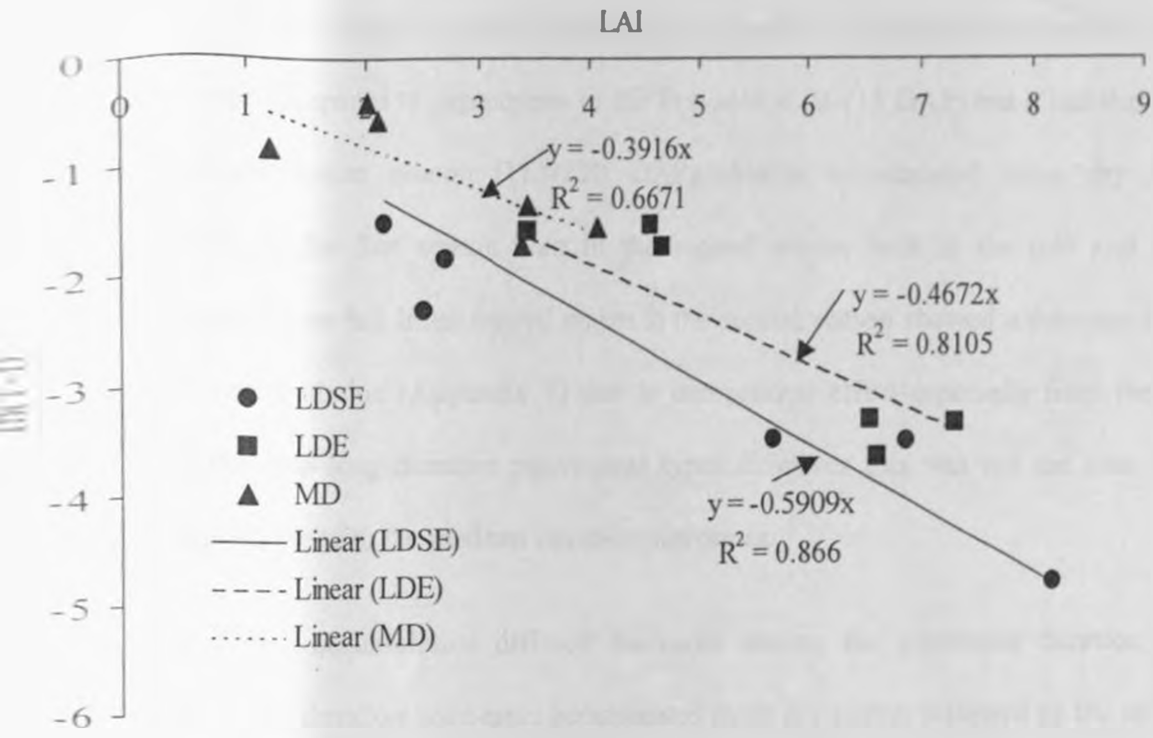


Figure 7. Relationship between LAI and the natural logarithim of the fractional of PAR transmitted through the canopies of MD = medium duration, LDE = long duration erect and LDSE = long duration semi-erect pigeonpea.

5.2.4 Total dry matter (TDM)

The total dry matter of maize and pigeonpea (sole and intercropped) increased over time from planting and reached a maximum at harvest (Figure 8). Maize accumulated dry matter at a faster rate compared to pigeonpeas in the first season (0-115 DAP) but it had the lowest in the second maize season (115-220 DAP). Maize accumulated more dry matter accumulation in the first season than in the second season both in the sole and in the intercropped (Figure 8a). Intercropped maize in the second season showed a decrease in total dry matter accumulation (Appendix 7) due to competition effect especially from the large canopy of the two long duration pigeonpeas types However this was not the case in the intercropped maize with the medium duration pigeonpea.

Total dry matter accumulation differed markedly among the pigeonpea duration types (Figure 8b). Long duration semi-erect accumulated more dry matter followed by the medium duration while the long duration erect pigeonpea had the least early in the season (0-115 DAP) due to poor establishment; but towards the end of the season (115-220 DAP) long duration erect accumulated the highest total dry matter. Intercropped pigeonpeas total dry matter accumulation was similar to sole cropped pigeonpea.

The relationship between total dry matter (TDM) and intercepted PAR is calculated using the equation below (Squire, 1990);

$$TDM = \varepsilon \sum_{0}^{i} Sf \qquad \textbf{Equation 13}$$

Where ε is the light conversion efficiency, S is the solar energy while f is the fraction of PAR intercepted.

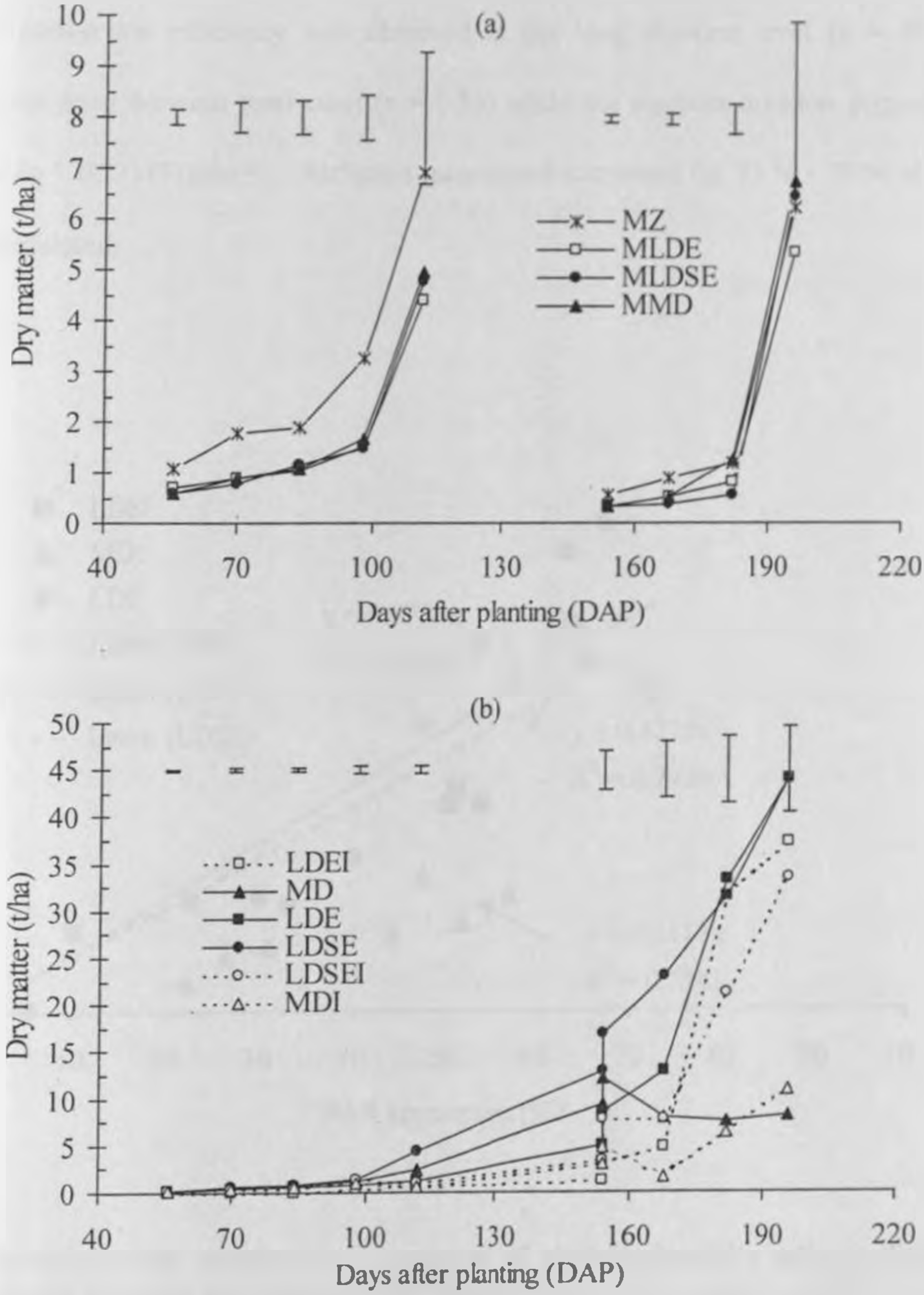


Figure 8. Change in total dry matter accumulation (kg/ha) over time for maize (a) and pigeonpea (b) in sole and intercrop at JKUAT, Thika. MZ = maize, MD = medium duration, LDSE = long duration semi-erect and LDE = long duration erect pigeonpea. MMD, MLDSE and MLDE represent maize intercropped with medium duration, long duration semi-erect and long duration erect pigeonpea respectively. MDI, LDSEI and LDEI represent medium duration, long duration semi erect and long duration erect intercropped with maize respectively. Bars represent LSD values (P=0.05).

The highest conversion efficiency was observed in the long duration erect (e = 0.58), followed by the long duration semi-erect (e = 0.53) while the medium duration pigeonpea had the least (e = 0.21) (Figure 9). Radiation intercepted accounted for 73 % - 79 % of the biomass accumulated.

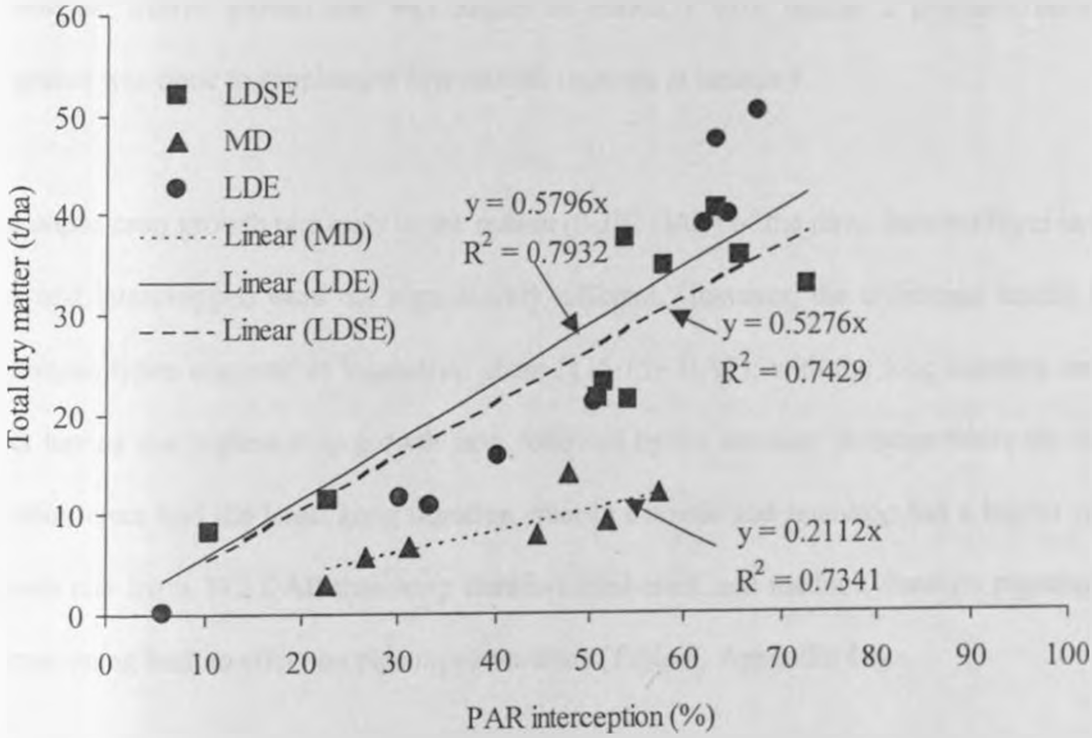


Figure 9. The relationship between the percentage of photosynthetically active radiation (PAR %) and total dry matter (TDM) of pigeonpea. MD = medium, LDSE = long duration semi-erect and LDE = long duration erect pigeonpea.

5.2.5 Crop growth rate (CGR)

Both maize and pigeonpea had a slow growth rate early in the season and a rapid growth rate from vegetative phase to the maturity stage (Table 7 and 8). At 88 and 60 DAP in the first and second maize season there were significant differences in the sole and the intercropped maize CGR (Table 7, Appendix 9). Maize intercropped with long duration erect and long duration semi-erect had low CGR compared to maize intercropped with the medium duration pigeonpea. Maize growth rate was higher in season 1 than season 2 probably because irrigation was done to supplement low rainfall received in season 1.

Pigeonpea crop growth rate early in the season (0-102 DAP) of the three duration types in the sole and intercropped were not significantly different. However, the difference among the pigeonpea types occurred at vegetative phase (115-159 DAP); with the long duration semi-erect having the highest crop growth rate, followed by the medium duration while the long duration erect had the least. Long duration erect in the sole and intercrop had a higher crop growth rate from 172 DAP than long duration semi-erect and medium duration pigeonpea. Intercropping had no effect on pigeonpea varieties (Table 8, Appendix 10).

Table 7. Crop growth rate (kg/ha/day) of maize (sole and intercrop) in season 1 and 2 at JKUAT, Thika.

Crop/DAP	Crop growth rate (kg/ha/day)							
	----------Season 1------------				----------Season 2----------			
	60-74	74-88	88-102	102-115	60-74	74-88	88-102	102-115
MZ	53.4	66.7	98.2	261	19.1	20.6	92	121
MMD	23.3	33.1	42.1	234	14.8	52.5	111	131
MLDSE	14	25.6	23.4	235	2.7	13.2	84	117
MLDE	6.2	10.3	36.2	205	12.6	22.8	45	108
SED	10.9	15.4	21.37	93.2	3.73	19.6	47	43.6

MZ = sole maize, whereas MMD, MLDSE and MLDE represent maize intercropped with medium duration, long duration semi-erect and long duration erect pigeonpea respectively. SED is the standard error of difference.

5.2.6 Grain yield

Maize grain yield in the sole crop system were not significantly different in the 2 seasons (Figure 10) probably because irrigation was done to supplement low rainfall received in season 1. The maize grain yields were 3578 and 3419 kg/ha in season 1 and 2 respectively. However results showed that maize grain yields were higher in the sole crop compared to the intercrop in both seasons (Appendix 15). Maize grain yield was less in the intercrop with the long duration pigeonpea types in season 2, because of competition effect of pigeonpea on maize. Intercrop with the medium duration showed an increase in maize grain yield in season 2 than in season 1.

Table 8. Crop growth rate (kg/ha/day) of three varieties of pigeonpea in the sole and intercrop system over time at JKUAT, Thika.

Cropping system	Variety/DAP	Crop growth rate (kg/ha/day)					
		60-74	74-88	88-102	102-115	115-159	159-172
Sole cropping	MD	15.6	21.1	41.6	77.4	497	190
	LDSE	24.3	26.6	41.6	211.3	609	282
	LDE	9.1	17.1	35.8	47.5	259	261
Intercrop	MD	22.1	22.2	25.4	43.2	160	132
	LDSE	16.5	25.6	60.2	96.0	219	262
	LDE	0.3	3.7	33.2	38.8	46	135
SED		12.6	7.7	18.9	24.8	130.6	161.7

MD = medium duration, LDSE = long duration semi-erect and LDE = long duration erect represent pigeonpea varieties. SED is the standard error of difference.

Pigeonpea grain yield varied significantly different among the maturity groups (Figure 10, Appendix 17). Among the three pigeonpea duration types, long duration erect had the highest grain yield, followed by the long duration semi-erect type and medium duration type was the lowest. The average grain yield at the end of the season was 4560, 3203 kg/ha and 2687 kg/ha for the long duration erect, long duration semi-erect and medium duration respectively. Intercropping pigeonpeas had no significant effect on pigeonpea grain yield.

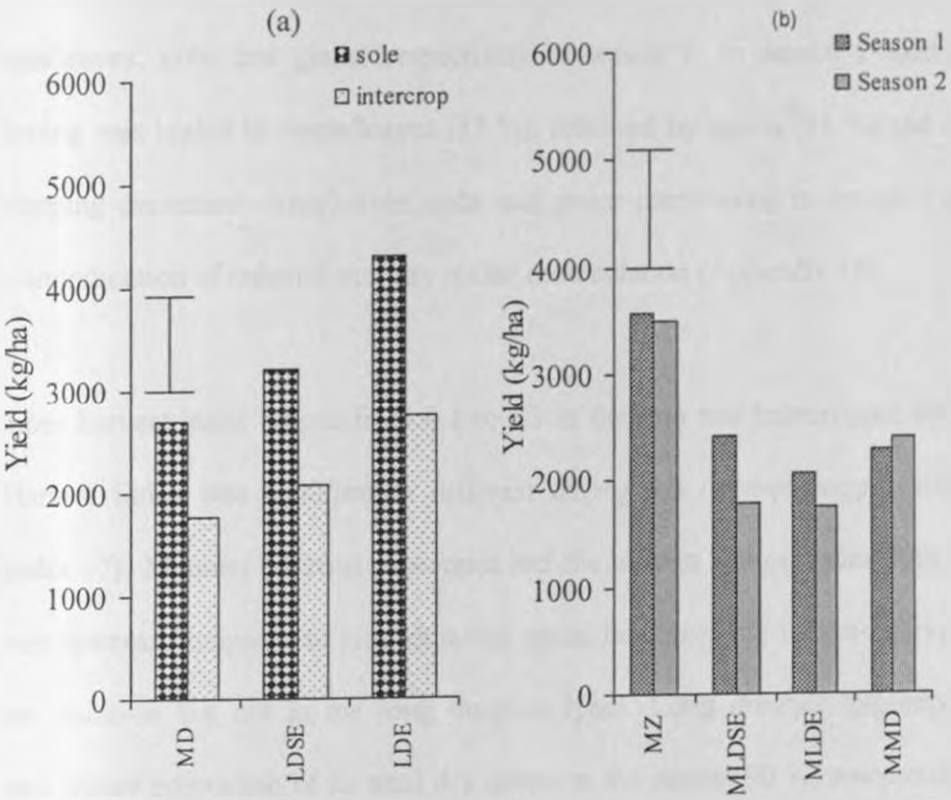


Figure 10. (a) Pigeonpea and (b) maize grain yield in the sole and the intercrop at JKUAT, Thika. MD = medium duration, LDSE = long duration semi-erect and LDE = long duration erect sole pigeonpea. MZ = maize sole whereas MLDSE, MLDE and MMD represent maize intercropped with long duration semi-erect, long duration erect and medium duration pigeonpea, respectively. Bars represent LSD values (P=0.05).

5.2.7 Harvest index (HI) and total dry matter partitioning

Maize harvest index (ratio of grain weight to total dry matter) was higher in season 1 than season 2 (Table 9). Maize allocated an average of 40 %, 14 % and 46 % of its total dry matter to stems/leaves, cobs and grains respectively in season 1. In season 2 total dry matter partitioning was higher in stems/leaves (55 %), followed by grains (41 %) and cobs (4 %). Intercropping decreased stems/leaves, cobs and grains partitioning in season 2 and harvest index, an indication of reduced total dry matter accumulation (Appendix 15).

Pigeonpea harvest index ranged from 0.1 to 0.3 in the sole and intercropped system (Table 10). Harvest index was significantly different among the three-pigeonpea maturity types (Appendix 17). Medium duration pigeonpea had the highest harvest index both in sole and intercrop systems compared to long duration types. Intercropping reduced harvest index in medium duration but not in the long duration types. Long duration pigeonpea varieties allocated higher proportion of its total dry matter to the stems (90 %) compared to grain (7 %) and husks (3 %) while the medium duration pigeonpea allocated 70 %, 5 % and 25 % to stems, husks and grains respectively. There was a significant difference of stems, husks and grains among pigeonpea varieties. Intercropping did not significantly influence total dry matter allocated to stems, husks and grains in all pigeonpea varieties.

Table 9. Harvest index and dry matter partitioning of stems, cobs and grains of maize (season 1 and 2) in the sole and intercropped system at JKUAT, Thika.

Season	Crop	Stem/leaves	Cob	Grain	TDM	HI
		(kg/ha)				
S 1	MZ	3008	1094	3578	7680	0.47
	MMD	2424	743	2276	5443	0.42
	MLDSE	1625	659	2418	4702	0.52
	MLDE	1734	588	2056	4378	0.47
	SED	892.1	122.6	522.5	772.7	0.1
S 2	MZ	2793	253	3491	6537	0.53
	MMD	3128	161	2384	5673	0.42
	MLDSE	3372	149	1782	5303	0.34
	MLDE	2808	140	1751	4699	0.37
	SED	717.9	36.6	393.9	1494.9	0.05

MZ = sole maize whereas MLDSE, MLDE and MMD represent maize intercropped with long duration semi-erect, long duration erect and medium duration pigeonpeas respectively. S1 = season 1, S2 = season 2, TDM = total dry matter and HI = harvest index. SED is the standard error of difference.

Table 10. Harvest index and dry matter partitioning of stems, husks and grains of three pigeonpea maturity types in the sole and intercropped system.

Cropping system	Variety	Stem+Leaves (kg/ha)	Husk (kg/ha)	Grain (kg/ha)	TDM (kg/ha)	HI
Sole crop	MD	5352	662	2687	8701	0.31
	LDSE	36866	950	3203	41019	0.08
	LDE	39641	1444	4317	45402	0.10
Intercrop	MD	8779	587	1766	11132	0.16
	LDSE	33770	535	2079	36384	0.06
	LDE	35957	1323	2746	40026	0.07
SED		3617.7	64.2	470.8	3591.2	0.05

MD = medium, LDSE = long duration semi-erect and LDE = long duration erect sole pigeonpea. TDM and HI represent total dry matter and harvest index respectively. SED is the standard error of difference. NB: Litter fall mass not added.

5.2.8 Land productivity

Land productivity was evaluated by using the land equivalent ratio (LER) index as shown in equation 5 (section 2.6). Pigeonpea intercropped with maize yielded less than in the sole crop. Land equivalent ratios were significantly different among the three-pigeonpea types. Medium duration pigeonpea had a higher LER compared to the two long duration types, an indication of the advantage of the intercrop of pigeonpea with maize. The land equivalent ratio (LER) was 1.23, 1.29 and 1.33 for the long duration erect, long duration semi-erect and medium duration pigeonpea respectively.

5.3. Soil water changes

5.3.1 Calibrations Equations

The calibration equations in Figure 11 were used to convert neutron counts/16 seconds to volumetric water content at different depths.

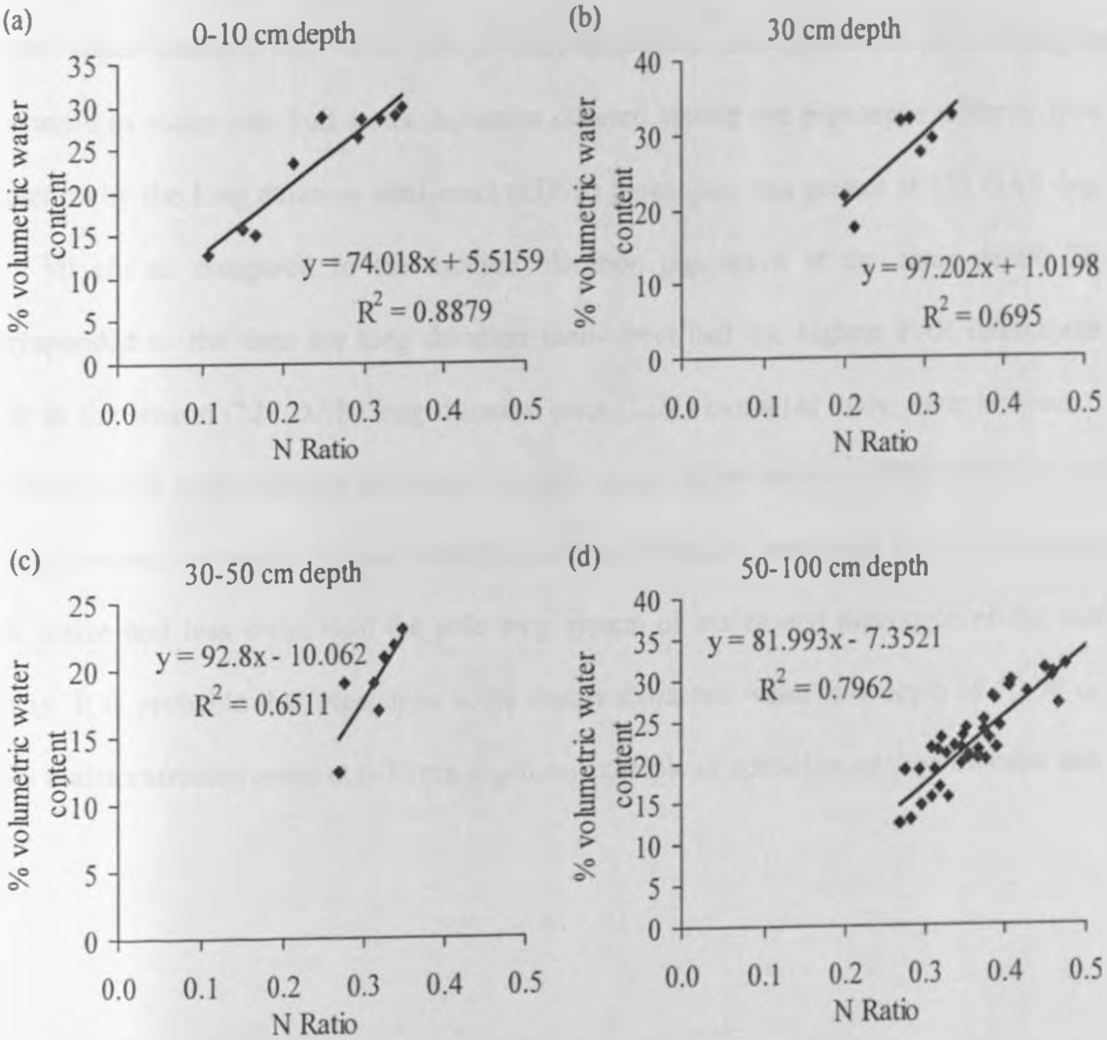


Figure 11. Calibration equations at various depths (a) 0-10 cm, (b) 30-50 cm, (c) 50-70 cm and (d) 70-90 cm, where N ratio is the neutron count in soil/ neutron count in water.

5.3.2 Soil water content changes

At 59 DAP maize extracted more water at 0 - 30 cm depth; probably at this stage the roots were concentrated in the top 30 cm (Figure 12). However, at the end of the first maize season (116 DAP) no soil water depletion occurred in maize plots when maize reached its physiological maturity but pigeonpeas especially the long duration semi-erect continued to extract water because they were still at their vegetative phase, an example of temporal separation in water use. Soil water depletion differed among the pigeonpea maturity types. Depletion by the long duration semi-erect (LDSE) pigeonpea was greater at 159 DAP depth 70 - 90 cm as compared to the medium duration pigeonpea at the same depth. This corresponded to the time the long duration semi- erect had the highest PAR interception. Later in the season (228 DAP) long duration erect (LDE) extracted more water between 70 and 90 cm than long duration semi-erect (LDSE) and medium duration (MD) which by then were harvested. soil water in plots intercropped long duration semi-erect (LDSE) pigeonpea with maize had less water than the sole crop system of maize and pigeonpea of the same variety. It is probable that pigeonpea roots readily extracted water to a depth of 70-90 cm; while maize extracted water at 0-30 cm depth, an example of spatial separation in water use.

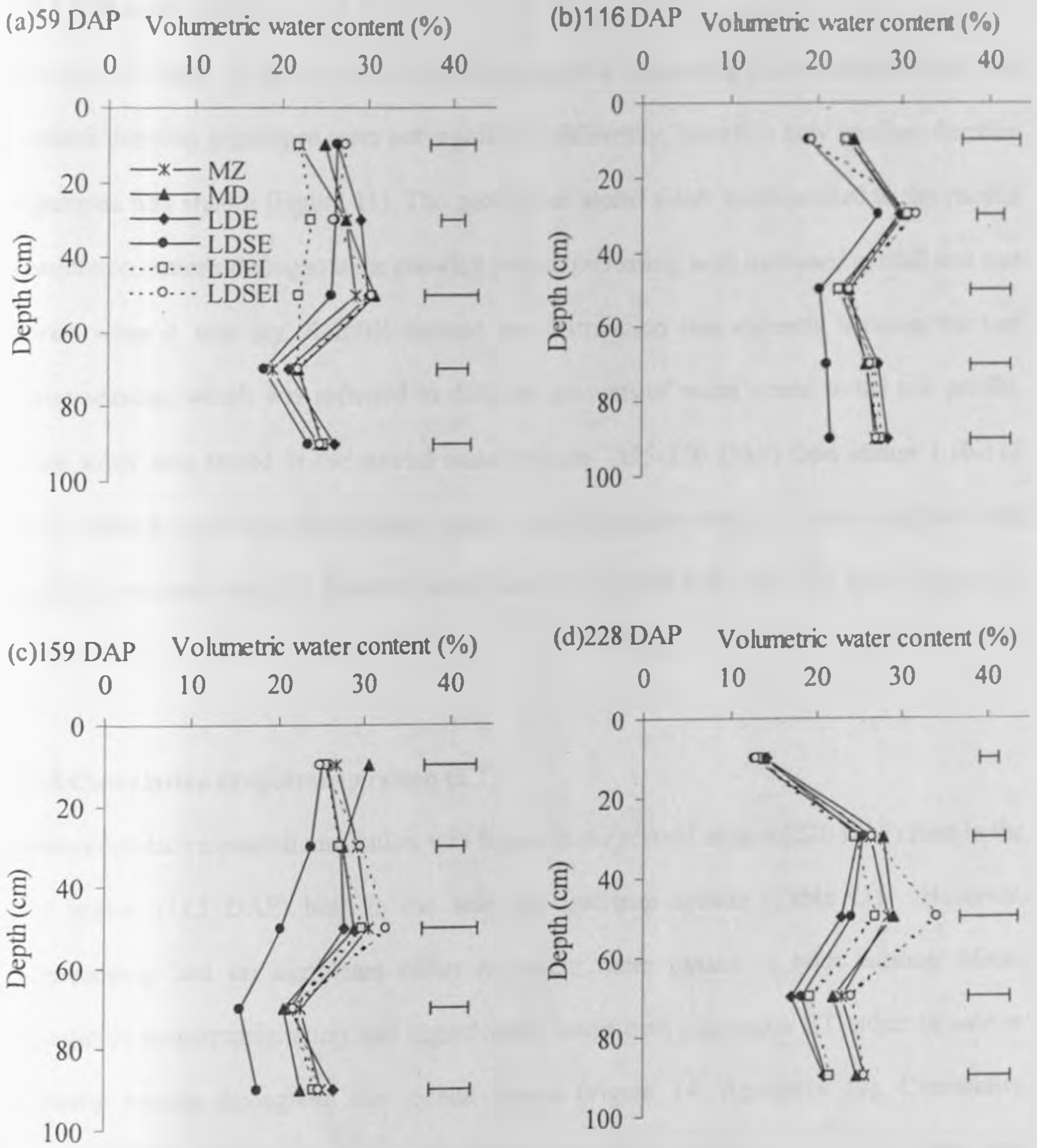


Figure 12. Volumetric water content (%) of sole and intercropped maize and Pigeonpea over time at JKUAT, Thika. At 59 DAP (maize tasseling stage), 116 DAP (after maize harvest), 159 DAP (pigeonpea flowering stage) and 228 DAP (second season maize harvest). MZ = maize, MD = medium duration, LDSE = long duration semi-erect and LDE = long duration erect pigeonpea whereas LDSEI and LDEI represents long duration semi-erect and long duration erect intercropped with maize respectively. Bars represent LSD values (P=0.05).

5.3.3 Soil water storage

Stored soil water in plots under long duration erect pigeonpea (sole and intercrop) and medium duration pigeonpea were not significant differently, therefore only medium duration pigeonpea was shown (Figure 13). The quantity of stored water corresponded to the rainfall distribution pattern throughout the growing period; increasing with increased rainfall and was lowest when it was dry. Rainfall amount and distribution was different between the two maize seasons, which was reflected in different amounts of water stored in the soil profile. More water was stored in the second maize season (115-220 DAP) than season 1 (0-115 DAP). Stored water was significantly lower in long duration semi erect sole crop than long duration erect and medium duration pigeonpea between 166 DAP and 172 DAP (Figure 13, Appendix 11).

5.3.4 Cumulative evapotranspiration (ET)

Maize cumulative evapotranspiration was higher in the second season (220 DAP) than in the first season (115 DAP) both in the sole and intercrop system (Table 11). However, intercropping had no significant effect on maize water uptake in both seasons. Maize cumulative evapotranspiration was significantly lower than pigeonpea ET either in sole or intercrop system throughout the second season (Figure 14, Appendix 12). Cumulative evapotranspiration was not significantly different among the pigeonpeas duration types both in the sole and intercrop system. Long duration erect (sole and intercrop) and long duration semi-erect intercrop water uptake was similar to the medium duration pigeonpea sole crop, therefore only medium duration pigeonpea sole crop is shown (Figure 14). Water uptake between maize and pigeonpea in the intercrop was similar to the sole crop system indicating that the competition between the two crops was minimal. Cumulative evapotranspiration increased over time for both maize and pigeonpea in the sole and intercropped system. The increase was slow during early stages when canopies were small, and increased at later stages of pigeonpea development when the canopies were large.

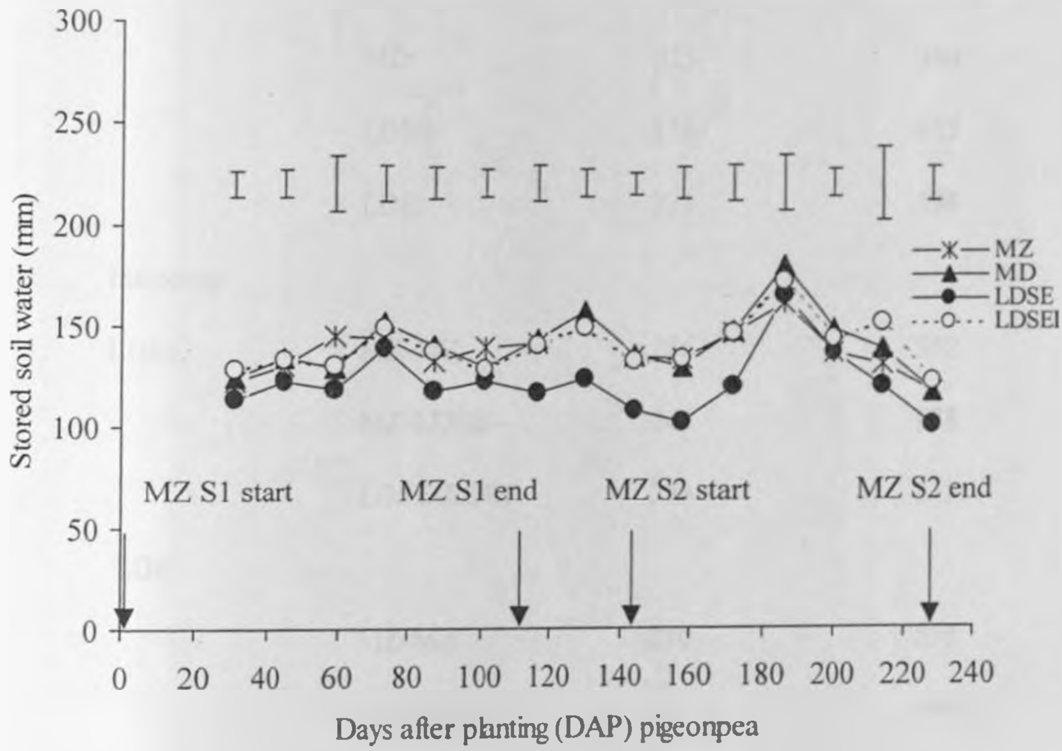


Figure 13. Seasonal change in stored soil water (mm) (0-90 cm depth) of maize and pigeonpeas in the sole and intercrop system over time at JKUAT, Thika. MZ = maize, MD = medium duration whereas LDSE and LDSEI represents long duration semi-erect sole and intercrop respectively. S1 and S2 is season 1 and season 2 respectively. Bars represent LSD values (P=0.05).

Table 11. Evapotranspiration (mm) of maize and three pigeonpea maturity types in sole and intercrop system at 115 and 220 DAP.

Cropping system/crop	Access tube position	ET(mm) 115 DAP	ET(mm) 220 DAP
Sole crop	MZ	260	551
	MD	235	880
	LDSE	251	885
	LDE	231	894
Intercrop			
LDSE	MZ-MZ	236	552
	MZ-LDSE	241	878
	LDSE-LDSE	253	875
LDE			
	MZ-MZ	230	559
	MZ-LDE	225	884
	LDE-LDE	240	896
SED		12.84	7.45

MZ represents access tube in maize sole crop whereas MZ-MZ represents access tube in maize intercropped with long duration semi-erect (LDSE) and long duration erect pigeonpea (LDE). MD, LDSE and LDSE is the access tube in medium duration, long duration semi-erect and long duration erect pigeonpea respectively in the sole crop. LDSE-LDSE and LDE-LDE is the access tube in long duration semi-erect and long duration erect pigeonpea in the intercrop system respectively. MZ-LDSE and MZ-LDE is the access tube between maize and pigeonpea. SED is the standard error of difference.

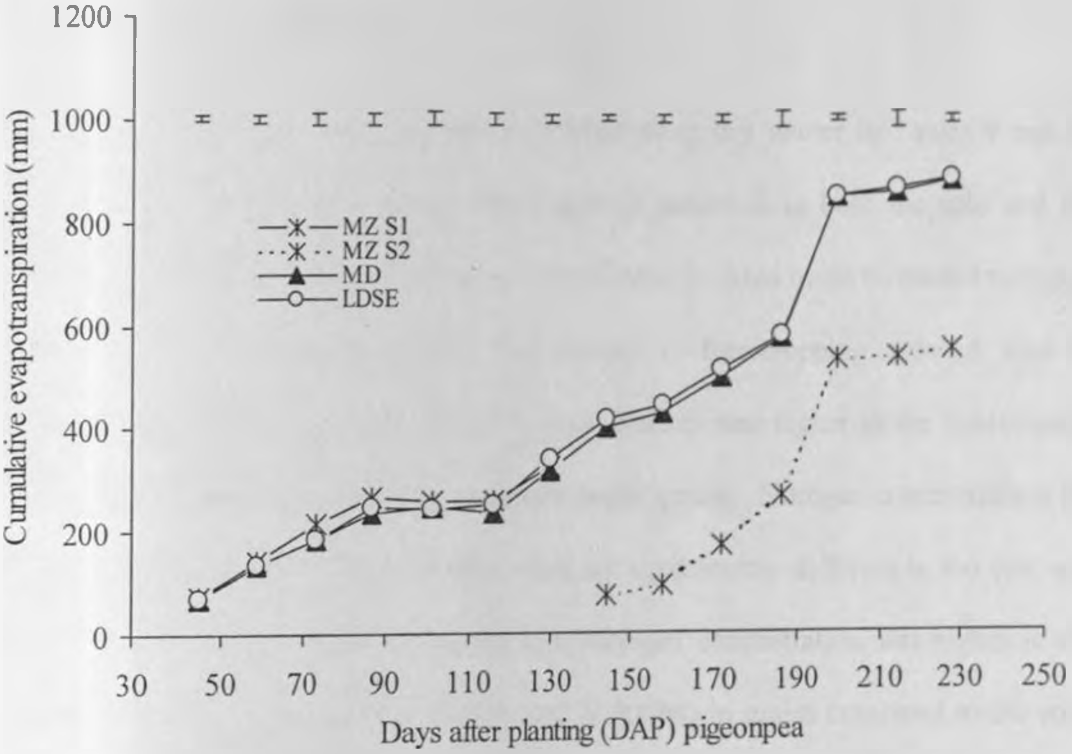


Figure 14. Cumulative evapotranspiration (mm) of maize and pigeonpeas in the sole crop system over time at JKUAT, Thika. MZ = maize, MD = medium duration and LDSE = long duration semi-erect pigeonpea. S1 and S2 is season 1 and 2 respectively. Bars represent LSD values (P=0.05).

5.4. Nitrogen uptake and partitioning

5.4.1 Plant nitrogen partitioning

Total N (kg/ha) in Tables 12 and 13 was calculated using dry matter in Tables 9 and 10 respectively. Total N uptake by maize was higher in season 2 in both the sole and the intercrop system compared to season 1 maize crop (Table 12). This could be related to higher N concentration in the second season than season 1. Intercropping reduced total N (kg/ha)uptake of maize in both seasons but N concentration was higher in the intercropped maize than sole maize, an indication of improved maize quality. Nitrogen concentrations for each component i.e. stems, cobs and grains were not significantly different in the sole and intercrop system in both seasons (Appendix 15). Nitrogen concentration was higher in the grain compared to stem and cob. The higher total N (kg/ha) in grains compared to the cobs and the stems in season 1 may be an indication of remobilization of N to grains. However, in season 2 stems/leaves had higher total N than season 1 that could be related to higher total dry matter allocated to stems/leaves. Maize produced less biomass and had low N concentration in comparison to pigeonpeas especially in the second season (115-220 DAP).

Pigeonpea N uptake increased between 115 DAP and 220 DAP but the amount differed among pigeonpea maturity types At 115 DAP long duration semi-erect had the highest total N uptake (81 kg N/ha) compared to the medium duration (47 kg N/ha) and long duration erect pigeonpeas (30 kg N/ha) (Table 13). However, at 220 DAP N uptake was highest in the long duration erect pigeonpea (1266 kg N/ha) and lowest in the medium duration variety (345 kg N/ha) (Table 14). Despite the high total N uptake of the long duration erect, it had the lowest N concentration in stems and husks but higher grain N concentration 4.5 %

compared to 3.6 % in the rest, Possibly an indication of efficient N remobilization to grain. Intercropping reduced total N uptake for the three-pigeonpea varieties at 115 and 220 DAP (Appendix 16 and 17) except for the medium duration at 220 DAP.

Stem and husk N concentrations were not significantly different while the total N (kg/ha) was significantly different among varieties. This could be a reflection of differences in total dry matter produced by the three varieties of pigeonpea. Grain N concentrations and total N (kg/ha) were significantly different among the three-pigeonpea types (Appendix 17). Despite the high concentration of N in the grains compared to the stems and the husks, stems had the highest total N (kg/ha) at the end of the season (Table 14). However long duration pigeonpea nitrogen concentrations in stem, husk and grain were not significantly different in the sole and intercrop system. Pigeonpea allocation of the total N uptake was 82 %, 2 % and 16 % to the stems/leaves, husks and grains respectively, excluding litter mass. This therefore means that stems left in the field will contribute to total N pool in the cropping system.

Table 12. Maize N partitioning (kg/ha) and nitrogen concentration [N] of cobs, grains and stems in the intercrop and sole crop at 115 and 220 DAP (JKUAT, Thika).

Cropping system		----N concentration %-----			------Amount of N (kg/ha)-------			
	Crop	Stem	Cob	Grain	Stem	Cob	Grain	Total
Season 1								
Sole crop	MZ	0.55	0.43	0.66	17.1	4.81	21.8	43.7
Intercrop	MMD	0.53	0.39	1.06	12.6	2.97	25.2	40.8
	MLDSE	0.48	0.26	0.99	7.7	1.69	24.7	34.1
	MLDE	0.52	0.27	1.17	8.8	1.49	18.7	29
	SED	0.06	0.11	0.21	5.58	1.22	5.96	5.58
Season 2								
Sole crop	MZ	1.61	1.15	1.05	42.9	3.11	29.5	75.5
Intercrop	MMD	1.38	1.10	1.66	34.7	1.91	32.9	69.5
	MLDSE	1.17	1.33	1.37	38.1	2.31	18.4	58.8
	MLDE	0.74	1.26	1.49	22.1	1.81	23.0	46.9
	SED	0.79	0.73	0.73	16.88	1.89	12.4	17.43

MZ is maize sole whereas MLDSE, MLDE and MMD represents, maize intercropped with long duration semi-erect, long duration erect and medium duration pigeonpea respectively. SED is the standard error of difference.

Table 13. Pigeonpea N partitioning (kg/ha) nitrogen concentration % N and Total N uptake of pigeonpeas in the intercrop and sole crop at 115 DAP at JKUAT, Thika

Cropping system	Variety	TDM	% N	Total N (kg/ha)
115 DAP				
Sole crop	MD	2310	2.02	46.7
	LDSE	4234	1.88	81
	LDE	1422	2.09	29.6
Intercrop	MD	629	2.02	12.6
	LDSE	1117	2.04	22.8
	LDE	657	2.01	13.9
	SED	513.0	0.15	11.47

MD = medium duration, LDSE = long duration semi-erect and LDE = long duration erect pigeonpea, TDM – total dry matter and % N = nitrogen concentration. SED is the standard error of difference.

Table 14. Pigeonpea N partitioning (kg/ha) and nitrogen concentration [N] of husks, grains and stems in the intercrop and sole crop at 220 DAP at JKUAT, Thika.

220 DAP		----N concentration %------			---Amount of N (kg/ha)--			TDM
		Stem+ leaves	Husk	Grain	Stem+ leaves	Husk	Grain	
Sole crop	MD	2.43	1.59	3.67	249	10.49	95.6	345
	LDSE	2.38	1.38	3.67	992	13.07	214.7	1220
	LDE	2.24	1.38	4.53	1046	19.74	200.6	1266
Intercrop	MD	2.3	1.35	3.61	268	7.99	65.5	341
	LDSE	1.68	1.39	2.33	623	7.45	52.9	683
	LDE	2.11	1.26	4.20	859	16.71	101.2	977
	SED	0.38	0.15	0.37	129.3	1.1	21.4	133.9

MD = medium duration, LDSE = long duration semi-erect and LDE = long duration erect pigeonpea, TDM = total dry matter, % N = nitrogen concentration. SED is the standard error of difference.

Pigeonpea nitrogen uptake of was higher than of maize. Nitrogen use differed among pigeonpea duration types, and was higher for the long duration erect, followed by the long duration semi-erect type while the medium duration type had the least. Intercropping maize and pigeonpea increased nitrogen uptake in the medium duration. This was not observed in the long duration semi-erect and long duration erect intercrop.

5.4.2 Soil mineral N

Soil mineral N had a slow steady increase from the beginning (before planting) of the season to 115 DAP (middle season) which was followed by a rapid increase from 115 DAP until the end of the season (220 DAP) in both the sole and the intercropped plots of maize and pigeonpea (Figure 15). The increase in mineral N coincided with high rainfall received at that time. Intercropping had no effect in the soil mineral N increase (Appendix 18).

In maize plots a significant difference in NH_4^+-N fraction and NO_3^--N from the middle season (115 DAP) to the end of the season (220 DAP) in all depths was observed (Figure 16). At 220 DAP most of the increase in soil mineral N was found in NH_4^+-N fraction compared to NO_3^--N fraction, probably maize preferential uptake was NO_3^--N compared to NH_4^+-N.

Long duration semi-erect (sole and intercrop) and long duration erect had similar trends, hence only long duration is shown in the diagram (Figure 17). NH_4^+-N fraction increased over time both in the sole and intercropped soil profiles of pigeonpea (Figure 16 a-d) except in the long duration erect intercrop, which showed a decrease from 115 DAP to 220 DAP, which was most pronounced at 50-100 cm depth (Figure 17 a).

NO_3^--N decreased from 115 DAP to 220 DAP in all the profiles of the long duration varieties (sole and intercrop) except at 50-100 cm depth in the long duration intercrop. This indicates that long duration erect preferred NH_4^+-N than NO_3^--N which was taken up by the maize crop.

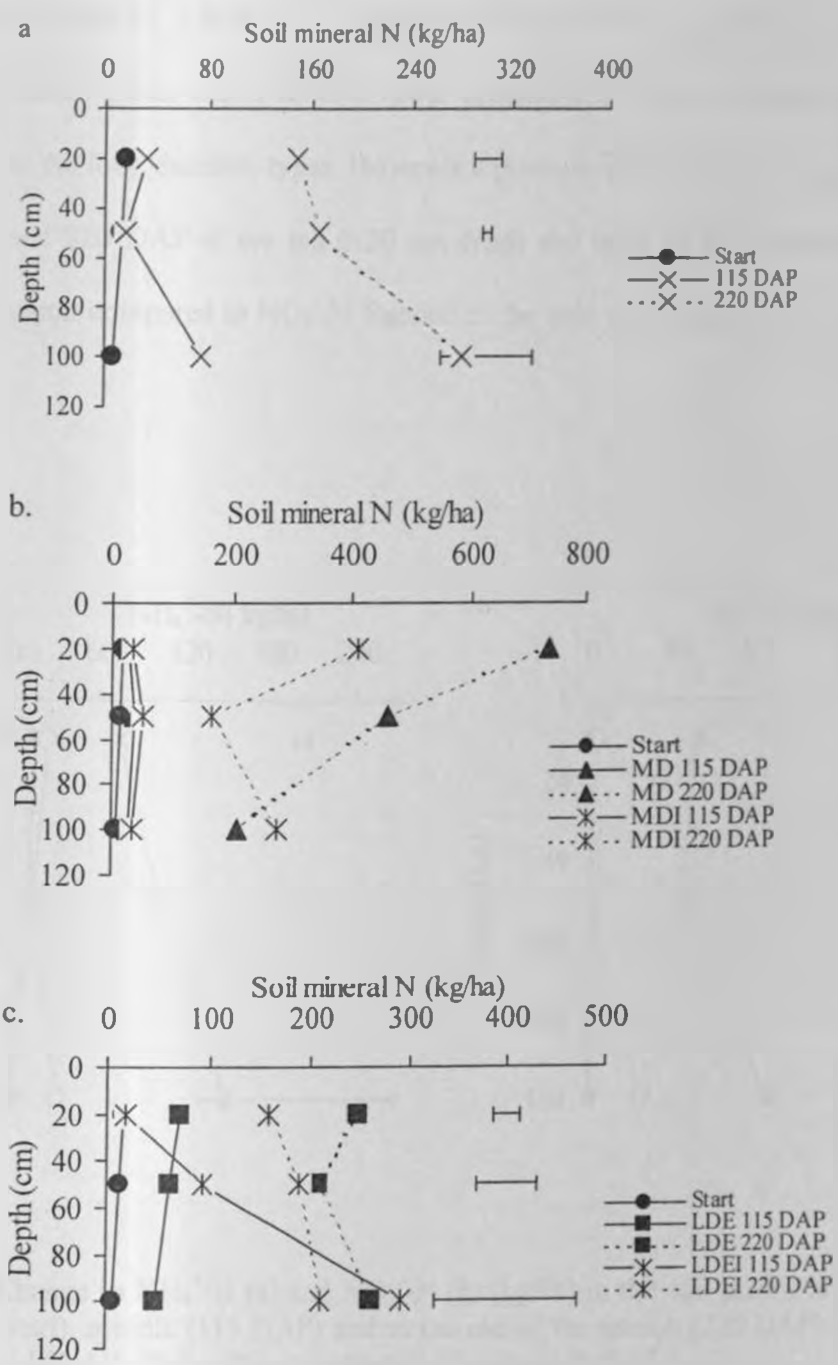


Figure 15. Soil mineral nitrogen (kg/ha) in the soil profile at the beginning (before planting), middle (115 DAP) and at the end of the season (220DAP) at depths; 0-20, 20-50 and 50-100 cm. a. b. and c represent maize, medium duration and long duration erect sole and intercropped plots respectively at JKUAT, Thika. Bars represent SED values (P=0.05).

The highest levels of N both NO_3^--N and $NH4^-$-N at 0-20 cm depth, were observed in the medium duration plots, which reflects lower demand of N or less efficient in N uptake as compared to the long duration types. However a pronounced increase was observed between 115 DAP and 220 DAP at the top 0-20 cm depth and most of the increase was found in NH_4^+-N fraction compared to NO_3^--N fraction in the sole crop than the intercrop (Figure 17 e-h).

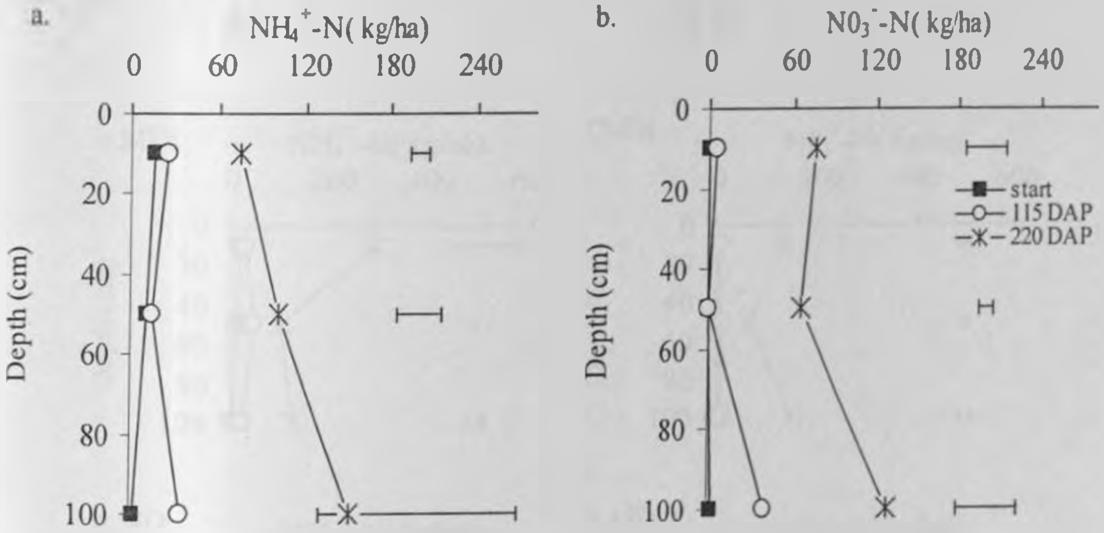


Figure 16. Change in NH_4^+-N (a) and NO_3^--N (b) (kg/ha) in the soil profile at the beginning (start), middle (115 DAP) and at the end of the season (220 DAP) in sole maize at JKUAT, Thika. Bars represent LSD values (P=0.05).

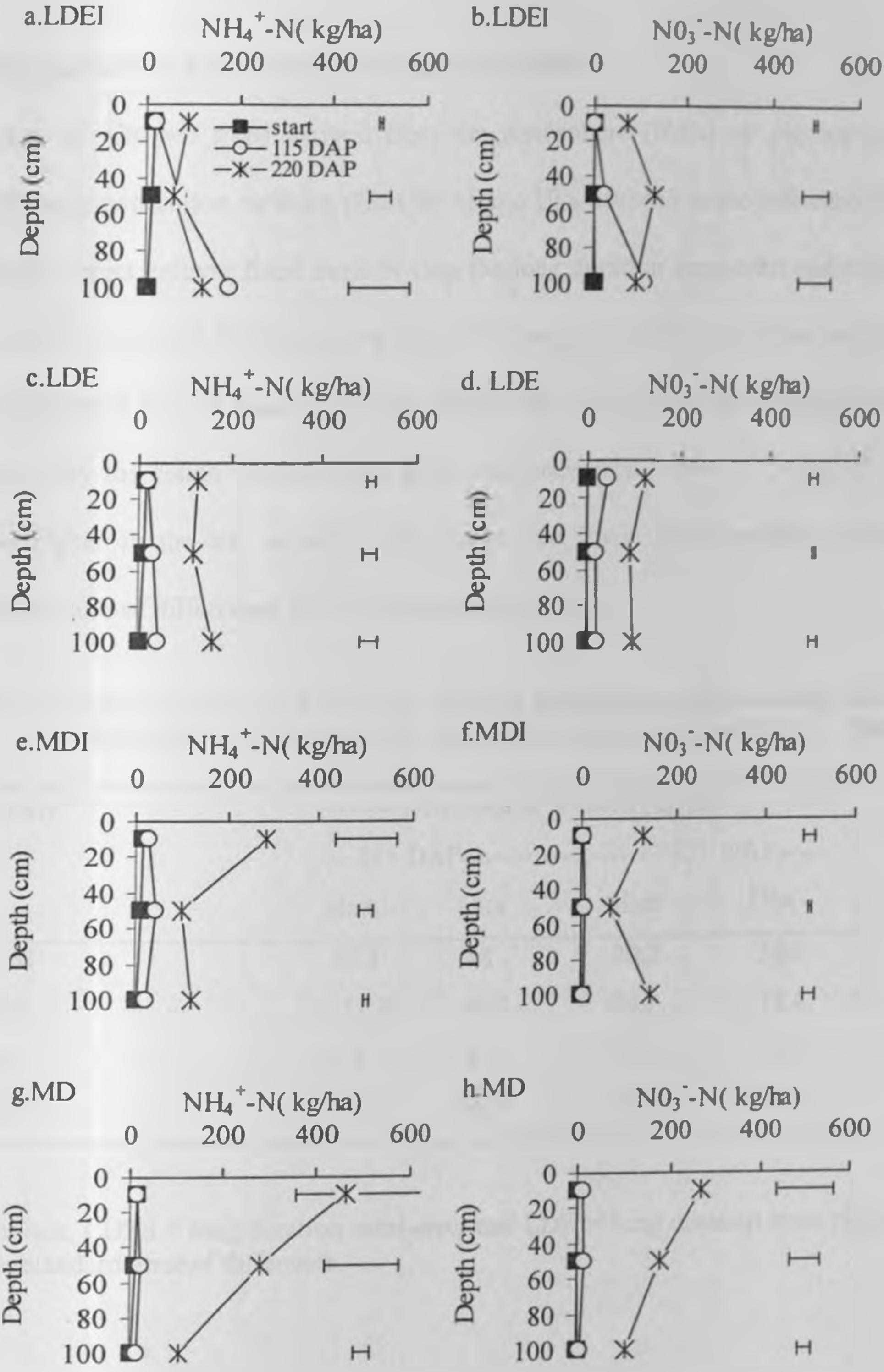


Figure 17. Change in NH_4^+-N and NO_3^--N (kg/ha) in the soil profile at the beginning (start), middle (115 DAP) and at the end of the season (220 DAP) at different depths in the sole and intercropped plots of pigeonpeas at JKUAT, Thika. (a) and (b) represents (NH_4^+-N and NO_3^--N) for long duration erect intercrop, (c) and (d) long duration erect sole crop, (e) and (f) medium duration intercrop,(g) and (h) medium duration sole crop respectively. Bars represent SED values (P=0.05).

5.4.3 Nitrogen derived from atmospheric fixation (Ndfa)

The amount of nitrogen fixed derived from the atmosphere (Ndfa) by pigeonpea was calculated using two cotton varieties (Hart 89 M and Uka 59/146) as the reference crops. Long duration erect cultivar fixed more N than the long duration semi-erect and medium duration cultivars at 220 DAP. Low values of N fixed by the long duration erect and medium duration at 115 DAP and 220 DAP respectively was probably due to high biomass accumulation by the cotton varieties used as the reference crop (Table 15). Amount of N fixed was higher in the late maturing pigeonpeas, and lower in the medium duration pigeonpea because of differences in the biomass accumulation.

Table 15. Estimated amount of N fixed by different pigeonpea varieties using two cotton varieties (Hart 89 M and Uka 59/146) as the reference crops at JKUAT, Thika.

Variety	-----------Amount of N fixed (kg/ha)-------------			
	----115 DAP-----------		--------220 DAP------	
	Hart	Uka	Hart	Uka
LDSE	39.1	48	39.2	38.4
LDE	-12.3	-9.8	74.2	73.4
MD	4.8	7.3	-12.2	-13
SED	15.9	44.0	14.8	14.8

MD = medium, LDSE = long duration semi-erect and LDE = long duration erect pigeonpea.
SED is the standard error of difference.

5.4.4 Litter fall

Amount of N contained in litter was measured during the growing season for the pigeonpea grown either sole or intercrop with maize. Pigeonpea varietal differences had an effect on the amount of litter fall (Table 16). Long duration erect produced the highest litter fall (Plate 3), followed by the long duration semi-erect type and medium duration type the lowest. The amount of litter fall in the sole crops was higher compared to the intercrop system.

Amount of N in the litter fall and nitrogen concentration was significantly different among the pigeonpea duration types. Long duration semi-erect and medium duration pigeonpea had similar [N] while long duration erect had the least, it is probable that a lot of N for the later was remobilized to the grains. However, long duration erect pigeonpea had the highest total N (kg/ha), followed by the long duration semi-erect and finally the medium duration pigeonpea. Despite the differences in the amount of litter fall (g/m^2) in the sole and in the intercrop the total N (kg/ha) was not significantly different for the three-pigeonpea varieties.

Table 16. Seasonal litter fall (kg/ha) and total N (kg/ha) of pigeonpea at JKUAT, Thika.

Cropping system	Pigeonpea variety	N %	Litter (kg/ha	Total N (kg/ha)
Sole crop	MD	2.30	2650	61
	LDSE	2.45	3870	94
	LDE	1.68	7600	132
Intercrop	MD	2.81	1760	50
	LDSE	2.82	3370	96
	LDE	1.8	5180	93
SED		0.3	698	21.1

MD = medium, LDSE = long duration semi-erect and LDE = long duration erect pigeonpea. N % represent nitrogen concentration. SED is the standard error of difference.

Plate 3. Long duration erect pigeonpea litter fall at JKUAT, Thika.

5.4.5 Summary of the N (kg/ha) budget

The source of N in maize plant was; soil mineral N and fertilizer N. Therefore N in an non fixing crop can be calculated using the equation below (Mburu, 1996);

$$Npl = Nf + Nsoil \qquad \textbf{Equation 14}$$

Where Npl is total plant uptake

Nf is N derived from fertilizer application and

Ns is N derived from soil mineral N supply.

Assuming that fertilizer N recovery in maize is 30 % (Pilbeam *et al.*, 1995), then N fertilizer for maize would be expected to be; applied fertilizer * % recovery by maize, i.e. 10*30/100= 3 kg/ha; hence N from soil for maize would be 43.7-3 = 40.7 kg/ha in season 1 while in season 2 would be 75.5-3 = 72.5 kg/ha. Therefore maize only took up 36 % and 13 % of the total N from the soil and about 64 % N and 87 % N was left in the soil in the first and the second season respectively, Probably most of the N was in the deeper layers of the soil (Figure 16) that was out of reach from maize roots concentrated at the top 0-30 cm.

Sources of N in a nitrogen fixing plant can be calculated as;

$$Npl = Ns + Ndfa + Nf \qquad \textbf{Equation 15}$$

Where Ndfa is the plant N derived from the atmospheric nitrogen fixation.

Since no fertilizer was applied to pigeonpea, then N sources include Ns and Ndfa.

Long duration erect and long duration semi erect pigeonpea fixed about 6% and 4% of the total N and took up 94% and 96% from the soil respectively. It is likely that part of the N may have been derived from litterfall, however this would not have exceeded 10% of the total N uptake. It is probable that N was recycled in the system through capture of soil N deep in the profile (Figure 17d). It was difficult to estimate Ndfa by the medium duration pigeonpea, however its seasonal N uptake was higher than that of maize but approximately 27% of the long duration pigeonpea types.

Table 17. Summary of the N (kg/ha) budget of maize and varieties of pigeonpea as sole crops at JKUAT, Thika.

Crop	Fert N	N soil	N dfa fixed	Total N
MZ S1	10	111.9	0	43.7
MZ S2	10	552	0	75.5
LDSE	*	766	39	1220
LDE	*	723	74	1266

MZ S1 and S2 is maize season 1 and 2 respectively whereas LDSE = long duration semi-erect and LDE = long duration erect pigeonpea. N fert is nitrogen in fertilizer, Ndfa is the amount of N fixed using the difference method and N soil is the soil mineral N. Data derived from Tables 12, 13, 14 and 15. * indicates that no fertilizer was applied to pigeonpeas.

5.5. Residual effect results

5.5.1 Residual effect of pigeonpea on subsequent maize growth

The grain yield, total N uptake and total biomass obtained from plots that were previously intercropped maize and pigeonpea were higher than plots with continuous maize crop except in the intercropped plots with the medium duration pigeonpea (Table 18, Appendix 19). However from the sole cropped plots of pigeonpea grain yield, total N uptake and total biomass were less than either the plots that were previously intercropped maize and pigeonpea or continuous crop of maize. The yield increased by about 15% from plots previously intercropped with long duration semi-erect and 4% for long duration erect than after maize, total N uptake and total biomass increased by about 39% from plots previously intercropped with long duration semi-erect and 14% for long duration erect pigeonpea than after maize. However, from the comparisons made on average total stems/leaves and cobs N uptake from different treatments, an increase was observed from the plots that were previously intercropped than plots with continuous maize crop except in the intercropped plots with the medium duration pigeonpea.

Table 18. Maize dry matter accumulation and N uptake grown after harvesting maize and pigeonpea at JKUAT, Thika.

Cropping system	Crop	Dry matter (kg/ha)				N uptake (kg/ha)			
		Stem	Cob	Grain	TDM	Stem	Cob	Grain	T N
Continuous plot	MZ	1187	450	2161	3380	19.1	5.98	35.9	54.2
Sole plots	MD	1302	412	1583	3297	21.0	5.49	26.3	52.7
	LDSE	863	322	1524	2200	13.9	4.17	25.3	35.4
	LDE	1744	555	1134	3576	28.1	6.98	18.9	57.1
Intercrop plots	MMD	1125	368	1917	3410	18.1	6.05	31.8	53.4
	MLDSE	1674	529	2506	4709	27.0	7.03	41.6	75.6
	MLDE	1476	575	2241	3870	23.8	7.64	37.2	61.8
	SED	296.3	88.2	403.6	696.7	88.2	1.00	6.70	11.54

MZ is sole maize whereas MLDSE, MLDE and MMD represent maize intercropped with long duration semi-erect, long duration erect and medium duration pigeonpea respectively. TN = total nitrogen uptake and TDM = total dry matter. SED is the standard error of difference.

5.5.2 Soil N% after the residual maize

Pigeonpea varietal differences had no significant difference on Soil N% (Appendix 19). Soil N% observed from the plots that were previously planted sole crop of medium duration (0.09 N%), long duration semi erect (0.09 N%) and long duration erect pigeonpea (0.11 N%) was higher than either intercropped plots of medium duration (0.08 N%), long duration semi erect (0.07 N%) and long duration erect pigeonpea (0.09 N%) or continuous plots of maize (0.08 N%).

5.6 Discussion

5.6.1 Crop phenology

Poor establishment of long duration erect pigeonpea appeared due to poor germination of the seeds that could be related to viability problem. Long duration pigeonpea tend to have poor germination as reported by Silim (personal communication). Variability in the duration for 50 % days to flower and physiological maturity of pigeonpea were attributed to the inherent characters of the pigeonpea cultivars used and may be also explained by differences in thermal duration of different phenological stages. Medium duration flowered and matured earlier than the long duration types (Silim *et al.,* 1995) and intercropping did not influence time of flowering and maturity for maize and pigeonpea.

Medium duration cultivar was shorter than long duration pigeonpea cultivars. Plant height is influenced by maturity duration, photoperiod and temperature (Reddy, 1990). Long duration cultivars are generally tall, because of their prolonged vegetative phase and the short-duration or early maturing varieties are short due to their short vegetative growth phase (Reddy, 1990). In the second maize season, maize was taller than the first maize season.

Possibly due to differences in total rainfall received. In the second season total rainfall received was 618 mm and in the first season was only 148 mm.

5.6.2 Leaf area index and PAR interception

PAR initially increased and then decreased over time. The decrease in the amount of PAR intercepted in maize and pigeonpea as the crop matured could be a reflection of leaf senescence. Differences in LAI among pigeonpea duration types could be attributed to morphological characteristics i.e. the highly branching types (long duration semi-erect) have higher LAI than the more compact medium duration type. The decline of LAI of the long duration semi-erect and medium duration pigeonpea was an indication of loss of leaf area in the later stages of reproductive growth indicating their earliness in phenology compared to the long duration erect which was still at its vegetative stage (171 DAP). Leaf fall at flowering, in the later stages of reproductive growth of pigeonpea have been reported (Thirathion *et al.*, 1987).

As maize and pigeonpea developed there were differences in light interception, which is a reflection of early rapid vegetative growth and higher leaf area index of maize and slow initial growth habit of pigeonpea, an indication of temporal separation in light use in the intercrop system (Figure 6). This is an example of temporal light use in the first maize season because of differences in maize and pigeonpea phenologies (Fukai and Trenbath, 1993). Pigeonpea dominated maize more in the second season than in the first season an indication of an increase in leaf area index and dry matter accumulation resulting in competition for light in the second season. Light interception was higher in the intercrop (170 DAP-Figure 6) than in the sole maize in the second maize season because the pigeonpea canopy was large hence intercepted more light. Intercropped pigeonpea, intercepted more light after maize harvest an indication of compensatory growth, which resulted in increased plant height and total dry matter accumulation.

Difference interception of PAR among the three-pigeonpea maturity types probably is a reflection of differences in LAI and canopy architecture. Long duration semi-erect had a higher K value (0.5) that may have contributed to higher light interception than long duration erect (K value 0.4) and medium duration (K value 0.2). This indicated that long duration semi-erect was more of a planophile that resulted into an increase in radiation interception during early vegetative phase while medium and long duration erect were erectrophilous (Figure 7). K values are lower for erectophile canopies and higher for planophiles canopies (Campbell and Van Evert, 1994). In addition to canopy architecture, differences in k values are also attributed to other factors including differences in overall plant height (Edmendes and Laffile, 1993) and leaf number (Dwyer *et al.*, 1992).

Long duration semi erect attained a maximum PAR interception (90 %) at 172 DAP, a time that it extracted more water from deeper layers of the soil because of the larger canopy. After 172 DAP, PAR started falling, probably because the crop had reached physiological maturity (Figure 5).

5.6.3 Total dry matter and crop growth rate

TDM of maize and pigeonpea both in the sole and the intercrop system increased over time as a result of photoassimilates fixed through photosynthesis. Lawlor (1990) reported that increase in dry matter of plants depends on the amount of photoassimilates fixed through photosynthesis. Similar biomass production by sole and intercropped pigeonpea is an indication that pigeonpea was not affected by intercropping. However maize intercropped with the long duration pigeonpea varieties in the second season produced less dry matter than the sole maize due to reduced light available to maize. Dry matter of intercropped maize with the medium duration pigeonpea was not affected because maize was taller, hence no light reduction for maize.

The differences in TDM among pigeonpea duration types were either due to differences in crop duration or differences in PAR interception or light efficiency (Figure 6). Differences in TDM among pigeonpea may be explained by the differences in PAR intercepted depending upon leaf area development and growth duration (Patel, 2000). Jean *et al.* (1996) and Squire (1990) also reported that differences in biomass production were controlled by the efficiency, with which intercepted radiation was converted to biomass. Total dry matter could also have been influenced by N uptake and moisture availability. Total dry accumulation and total N uptake increases with increasing rate of nitrogen (Wilson *et al.*, 1994).

Differences in TDM of maize and pigeonpea may have been attributed to differences in photosynthetic pathway where by C4 plants (maize) have faster crop growth rate and produce dry matter more rapidly than the C3 plants (pigeonpea) (Tables 7 and 8). The crop growth rate of pigeonpea seedlings was relatively slow early in the season (2.4 g/ m^2/day) for long duration and 1.5 g/ m^2/day for the medium duration) compared to maize (4.9 g/m^2/day). The low initial crop growth rate of pigeonpea relative to many other crops has been reported by Muchow (1985). The low crop growth rate was possibly because of a smaller assimilatory surface indicated by low interception of radiation of pigeonpea seedlings (Lawn and Treodson, 1990). The maximum crop growth rate attained for maize was 26.1 g/m^2/day, which is low compared to the maximum CGR range reported for maize elsewhere 52 g/m^2/day (Brake, 1984) while for pigeonpea (60.9 g/m^2/day) was higher compared to peanuts 28 g/m^2/day (Brake, 1984). Rapid growth rate occurs as the crop develops, leaf area index expands and more light intercepted by the crop.

High correlation between total dry matter and percentage PAR intercepted is a reflection of the efficiency of the canopy to convert solar radiation intercepted into dry matter. Similar findings were reported by Mati (2000) that the high correlation between total dry matter and percentage PAR intercepted indicates, that dry matter produced was directly proportion to subsequent fractional radiation. Squire (1990) and Soetedjo (1998) also reported that the rate of dry matter production is proportional to the total amount of the incoming radiation that is intercepted and the efficiency with which it is converted to dry matter by the canopy.

5.6.4 Grain yield and harvest index (HI)

Maize grain yield in the sole crop system was similar in the two seasons. The grain yield of maize intercropped with long duration pigeonpea types was lower than that intercropped with medium duration pigeonpea probably because of larger canopy of the former that reduced the light available, hence decreased yields. Differences in yield among the pigeonpea duration types could be due to differences in the amount of light intercepted, N uptake and moisture availability. Long duration erect pigeonpea had higher yield, which could be attributed to longer light interception period, higher N uptake and water extraction from deeper layers hence high accumulation of dry matter. Total yield are generally affected by nutrients and moisture availability (Lenga, 1979). The differences in biomass and seed yield among pigeonpea duration types were largely ascribed to total PAR intercepted and dry matter produced (Patel *et al.*, 2000).

Harvest index for pigeonpea ranged between 0.1-0.3, which is comparable to values, reported for medium duration (0.21) (Rao *et al.*, 1984) and 0.17-0.24 (Rao and Willey, 1981) for the long duration pigeonpea. Harvest index of pigeonpea was relatively low compared to maize (0.29-0.56) and other legumes such as beans 0.4 (Mburu, 1996). Low pigeonpea HI is to be expected because the crop is indeterminate in growth habit, where during later growth stages, there is a continued production of reproductive and vegetative growth. The relationship between grain yield and individual components was most strongly correlated with total dry matter (Silim and Saxena, 1992). Studies with chickpea (Saxena *et al.*, 1990) have similarly shown that production of high total dry matter is one of the most prerequisites for attaining high grain yield. Differences in HI among the pigeonpea duration types could be attributed to differences in grain yields and biomass accumulation. Silim and Saxena (1992) reported that the cultivars that attained the highest grain yield had the highest total dry matter. Therefore it can be concluded that low grain yield of the medium duration cultivar was due to its low total dry matter accumulation.

Higher yields of the long duration erect could also be associated to the depth of the root system that appeared to influence uptake and utilization of soil water and nutrients (Figure 11). Long duration erect pigeonpea type had the greatest yield increase because it took more water from deep soil horizons than maize and medium duration pigeonpea (Figure 11). Aina and Fapohund (1986) reported that better performance of long duration varieties of pigeonpea was attributed to the development of a more active and deep rooting system and could also be positively correlated with crop duration. Medium duration pigeonpea had low yields; probably it was not able to utilize water from deeper layers because the roots were concentrated from 0-50 cm depth. Bahman and Maranville (1993) found out that shallow rooted genotypes were not able to effectively utilize soil moisture.

Land equivalent ratio ranged from 1.23-1.33 in maize- pigeonpea intercrop system indicating that intercrops were 23-33 % more productive than the sole crop. The range of LER in the study are comparable to other findings reported by Ali (1990) that LER in cereal based intercrops varied from 1.4 (with sorghum) to 1.8 (with pearl millet).

5.6.5 Soil water content changes

Soil moisture content generally decreased over time in the growing season. The changes in profile water content could be attributed to a combination of soil evaporation, transpiration, or crop water uptake. Differences in soil water depletion between maize and pigeonpea were more evident probably because of differences in crop growth and rooting characteristics, an example of spatial separation in water uptake in the intercrop, particularly of the long duration semi-erect. Pigeonpea roots readily extracted water to a depth of 70 - 90 cm while maize extracted 30-50 cm depth, indicating the respective rooting depths of the two crops, which were confirmed by the results of the greenhouse experiment.

At 59 DAP maize extracted more water than pigeonpea in the sole and intercrop at a depth of 30-50 cm because it was at full vegetative stage and therefore it was at its peak water needs compared to the much smaller pigeonpea canopy. However at the end of the first maize season (115 DAP) soil water content became constant during maturity stage, an indication that no soil water depletion occurred beyond maize maturity stage. Conversely, soil water continued to decline under pigeonpea, which was actively growing during that period, an example of temporal variation in water use.

Soil water depletion by the long duration semi-erect was greater at the depth of 70 - 90 cm later in the season (172 DAP) as compared to the medium duration pigeonpea. This indicated that long duration semi-erect pigeonpea had more roots deeper in the soil profile that were efficient in the extraction of the available soil water than the roots of medium duration. This agrees with Lawn and Troedson (1990) that later maturing genotypes have deeper root penetration than earlier genotypes.

The competition for soil water between the maize and pigeonpea in the intercrop was minimal because pigeonpea depleted soil water faster by exploring the deeper layers while maize depleted water at the top layers hence spatial variation in water use (115 DAP). This is in agreement with Willey (1979); Garba and Renard (1991) that an intercrop of legumes with a cereal may use water more efficiently than a monocrop of either species exploring a larger total soil volume for water, especially if the component crops have different rooting patterns.

5.6.6 Stored water

More water was stored at the later stages of pigeonpea, probably reflecting the amount of rainfall that was received. Results also showed that the soil profile in long duration pigeonpea had less stored water than the medium duration pigeonpea. The difference among pigeonpea varieties in stored water was due to long duration semi-erect extracting more water than the medium duration pigeonpea.

5.6.7 Cumulative evapotranspiration (ET)

Maize ET values observed in season 1 (260 mm) and season 2 (551 mm) showed seasonal variability. Seasonal ET variations for maize (518.4 and 619 mm) during short and long rains respectively has also been reported by (Lenga, 1979). Higher ET observed at later stages of development of pigeonpea compared to maize crop, could be related to the large canopy of pigeonpea hence more water was transpired from the plant decreasing the rate of soil evaporation. Similar findings were reported by (Mburu, 1996) that the rate of increase of ET was relatively slow during early stages when canopies were small, increased mid season and tailed off towards physiological maturity of the crop. Garabet (1995) also reported that larger canopy, result in a lower water amount evaporated from the soil surface and larger amounts could be then transpired by the plant. Pilbeam (1995) reported that when the plant canopy is large, and its duration is long, evaporation losses from the soil surface are often small, and transpiration losses are greater. Maize and pigeonpea water uptake in the intercrop was similar to the sole crop system, probably competition for water was minimal following the intercropping arrangement of three rows of maize interspersed with two rows of pigeonpea.

5.6.8 Nitrogen uptake and dry matter partitioning

Total N uptake of maize and pigeonpea increased significantly with increasing rate of plant biomass. Maize took more N in the second season compared to the first season, probably because of higher soil moisture permitted maize to absorb more N, which is reflected by the soil content in the soil profile. Maize intercropped with the long duration erect and semi-erect significantly influenced N uptake, however this was not observed in maize intercropped with medium duration pigeonpea. This could be attributed to larger canopy of the former than the latter reducing dry matter accumulation hence low N uptake of maize. Intercropping increased maize grain concentration compared to sole maize, indication of nutritional quality improvement. Pigeonpea had higher N uptake than maize probably due to capture of soil N deep in the profile and self fertililization from the litterfall and to a less extent from biological N fixation.

Total N (kg/ha) in long duration pigeonpea (1266 kg N/ha) was significantly higher (P = 0.01) than that of medium duration pigeonpea (345 kg N/ha) at the end of the season due to differences in the amount of biomass accumulated. Total N of legumes is related to maturity other than the location or the season (Taylor *et al.*, 1982), and the early duration of the medium duration may have been responsible for the lower N. The range of pigeonpea total N uptake was relatively higher compared to other legumes such as red clover hairy vetch (25 to 81 kg/ha; Scott *et al.*, 1987), alfalfa and red clover (54 to 73 kg/ha; (Holderbaum *et al.*, 1990) probably because of high biomass accumulation over a long period of time.

Though pigeonpea grain had higher N concentrations (3 to 4%) than stems (1.65-2.99%), stems had the highest total N yield due to high biomass accumulation. N uptake depended more on dry matter production rather than to changes in N concentration, indicating that dry matter yield is the overriding factor influencing total N uptake, rather than N concentration (Holderbaum *et al.*, 1990). The long duration erect pigeonpea had the lowest N concentrations in the stems/leaves, husks and litter mass (Table 14 and 16) but the highest grain N concentrations, indicating a higher remobilization of N to grain than the medium duration and long duration semi-erect.

Pigeonpea allocated 75%, of its total N uptake to stems and leaves, If 20% was allocated to leaves, then 55% of total plant N would be allocated to stem. If the stems are used as firewood by small-scale farmers, this would mean that 55% N would be lost from the system. Incorporating stems into the soil would improve soil fertility although the N in stems would be released slowly because of high lignin content in stems. If husks are used as animal feed and grains sold, then 3% and 8% N would be lost from the system. Therefore only 14% of the total N taken up by pigeonpea allocated to leaves is returned back to the soil through litter fall (Figure 18). Allowing pigeonpea stem to decompose would therefore play a vital role in farm N economy. Using the stem as livestock beddings may enhance stem N release.

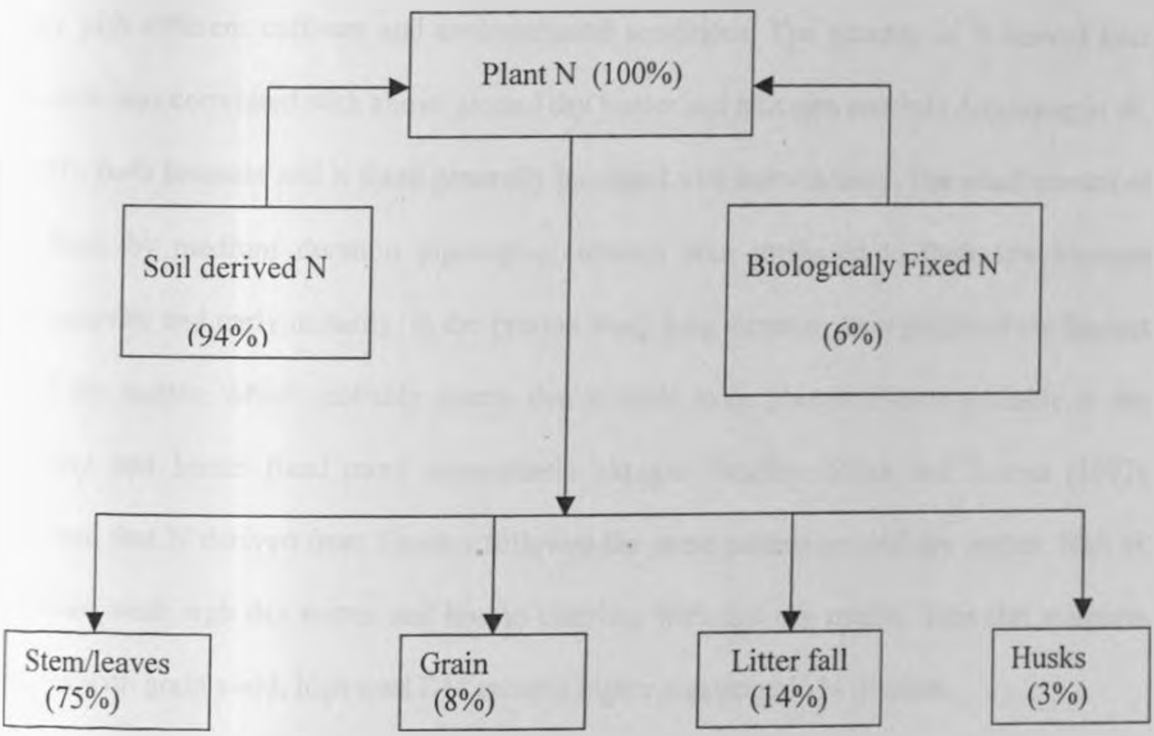


Figure 18. Summary of long duration erect pigeonpea N sources and partitioning under semi-arid conditions at JKUAT, Thika.

5.6.9 Nitrogen derived from atmospheric fixation (Ndfa)

Long duration cultivars fixed more N (39 - 74 kg/ha) than the medium duration (4.8-7.3 kg/ha) (Table 15). This could be attributed to high biomass production, which resulted to high amount of N contribution to the soil by the long duration pigeonpeas. These results corroborate findings of (Kumar-Rao, 1990) that long duration varieties fix more N than early maturity groups. It can be concluded that long duration pigeonpea fixed 81 % more than the medium duration pigeonpea. The Ndfa in medium duration pigeonpea was unreliable because the reference crop (cotton) grew too large hence underestimated the amount of N fixed. Mapfupo, *et al.* (1999) reported that on average, long duration cultivars fixed 23 % more than the medium duration type. The values are within the range of Armstrong *et al.* (1997) findings that the amount of N fixed by the pigeonpea was more than 60 kg N/ha, which may vary with different cultivars and environmental conditions. The quantity of N derived from fixation was correlated with above ground dry matter and nitrogen content (Armstrong *et al.*, 1997). Both biomass and N fixed generally increased with late maturity. The small amount of N fixed by medium duration pigeonpea cultivars was attributed to their low biomass productivity and early maturity. In the present study long duration erect produced the highest total dry matter, which probably means that it made more photosynthates available to the nodules and hence fixed more atmospheric nitrogen fixation. Silim and Saxena (1992) reported that N derived from fixation followed the same pattern as total dry matter, high in cultivars with high dry matter and low in cultivars with low dry matter. This also suggests that as with grain yield, high total DM ensures higher atmospheric N fixation.

5.6.10 Litter fall

Litter fall for the long duration varieties ranged from 3.9-7.6 t/ha but medium duration had 2.7 t/ha (Table 16). Intercropping reduced litter fall because of lower plant population density in the intercrop compared to sole crop. The sole and the intercrop of long duration erect pigeonpea had higher leaf fall than either the long duration semi-erect or the medium duration pigeonpea. This is an indication of excessive late season litter fall as from 186 DAP (Figure 6). Total N (kg/ha) supply expected from litter fall, based on litter biomass and nitrogen concentration % N ranged from 56-132 kg N/ha with the long duration erect having the highest N (kg/ha), therefore having a substantial contribution to soil fertility through litter decomposition.

5.6.11 Soil mineral N

During the growing season as from 115-220 DAP, the amount of soil available N increased in the soil (Figure 14). This may be attributable to increase in mineralization that could be related to increased rainfall as from 130 DAP to 200 DAP (Figure 3a). Soil mineral N has been reported to increase with increasing soil water content (Ma *et al.*, 1999).
Most of the increase in soil mineral N in maize plots was found in NH_4^+-N fraction compared to NO_3^--N fraction, probably maize preferential uptake was NO_3^--N (Figure 15). However NO_3^--N increased from 115 DAP to 220 DAP at 50-100 cm depth in the long duration intercrop (Figure 16 a-b) showed that long duration erect preferred NH_4^+-N than NO_3^--N, which was taken up by the maize crop thus minimum competition for nutrients in the intercrop. In medium duration pigeonpea plots, most of the increase was found in NH_4^+-N fraction compared to NO_3^--N fraction in the sole crop than the intercrop (Figure 16 e-h). In the intercrop, it was probable that maize took up more N resulting into higher plant N uptake (70 kg N/ha) than maize intercropped with the long duration types (50 kg N /ha).

Low NO_3^--N concentrations at the top 0-20 cm soil layer compared to NH_4^+-N ions could be explained by preferential uptake of nitrates than ammonium by crops or losses through leaching (Figures 15 and 16). Nitrate ions occur more readily in soil solution than ammonium ions (Brady, 1990; Tisdale *et al.*, 1990). Nitrate ions move freely to the plant root either by diffusion or mass flow and most of the plant absorbed nitrogen in this form (Tisdale *et al.*, 1990). Dou (1994) also reported that low nitrate concentration in the 25-45 cm soil layer could be due to nitrate losses through denitrification or leaching.

The increase of soil mineral N could also be associated to rapid decomposition of the litter fall. Litter fall contributed by pigeonpeas ranged from 50-132 N kg/ha (Table 16). The values in the study were relatively higher than other findings reported by Noordwijk *et al.* (1992) that the total N recycling in fallen leaves represents about 40 N kg/ha per growing season.

5.6.12 Residual effect of pigeonpea on subsequent maize growth

Maize grain yield, total N uptake and total biomass obtained from plots that were previously intercropped were higher than plots with continuous maize crop except in the intercropped plots with the medium duration pigeonpea (Table 18). The increase may be related to the N added in the soil through decomposition of the litterfall and from this study the amount of N from litter fall ranged from 50-132 kg N/ha. Sheldrake and Narayayan (1979) showed that a substantial amount of nitrogen (32 to 36 kg N /ha) was present in leaf fall. Chalk *et al.* (1993) reported that nitrogen is a major factor benefiting cereals following legumes compared with cereals following non-legumes. Kumar and Goh (2000) also reported that the magnitude of the yield increase of the subsequent crop is related to the amount of material returned to the soil.

Despite the high litter fall of the sole cropped pigeonpea compared to the intercrops, low grain yields and total dry matter of maize from the former plots could be attributed to the reduced light interception by the ratton crop of pigeonpea or probably the litter was not confined to one place where it was produced. High soil N % from the plots that were previously planted sole crops of pigeonpea compared to the intercropped plots may be due to differences in litter fall that was attributed by differences in population density. Long duration erect had the highest soil N %, which may be explained by high litter fall and biomass accumulation.

From the study, maize grain yield increased by about 15% in the plots previously intercropped with long duration semi-erect and by 4% for long duration erect than after maize. Total N uptake and total biomass increased by about 39% in the plots previously intercropped with long duration semi-erect and 14% for long duration erect crop. Other findings showed that a medium duration pigeonpea grown as a sole crop had a large residual effect on the following maize crop, increasing grain yield by 57% and total biomass by 32% compared to a fallow treatment (Kumar-Rao *et al.*, 1983) and it was estimated that pigeonpea had a beneficial effect on maize equivalent to about 40 kg N/ha. The amount of N leaves that fall during growth of long duration pigeonpea may be as much as 68-84 kg N /ha (Kumar-Rao *et al.*, 1996).

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

Cotton and pigeonpea had similar rooting characteristics and biomass accumulation; an indication of its suitability as a reference crop for determining and quantifying the amount of nitrogen fixed by the long duration pigeonpea using the difference method. Maize and sorghum may over estimate the amount of nitrogen fixed because of differences in rooting characteristics and growth higher growth rates because they are C_4 plants.

Cotton reasonably estimated N fixed by long duration pigeonpea but it was difficult to estimate the amount of N fixed by the medium duration pigeonpea because cotton accumulated more biomass hence underestimated amount of N fixed. Therefore a more reliable method is required to estimate the amount of N fixed especially for medium duration pigeonpea. Long duration pigeonpea plays an important role in low input maize production systems primarily through N cycling (probably through capture of deep soil N pool and litter) and to a lesser extent through biological nitrogen fixation and this improves maize yield and quality. Long duration pigeonpea varieties had higher yields than medium duration, therefore the former have the potential to improve food security and economy in semi-arid areas.

There was temporal separation in light interception by maize and pigeonpea in the intercrop due to slow early pigeonpea growth but rapid maize growth resulting in little competition between the two crops and hence maize yields were unaffected.

There was complimentarily in water use through spatial separation due to differences in rooting characteristics (maize has shallow roots while pigeonpea is a deep rooted crop) and temporal separation due to differences in growth rates of the crops.

Nitrogen use was more advantageous in the intercrop than sole crop system especially in maize- medium duration pigeonpea intercrop. Intercropping also increased maize grain N concentration compared to sole maize, indication of nutritional quality improvement. Soil mineral N increased with time, an indication of pigeonpea contributing N either through decomposition of litter fall and/or recycling from deep soil horizons.

LER in the maize-pigeonpea intercrop was greater than 1, which showed intercropping advantage that encourages maximization of land use. Higher maize yields in season 1 than season 2 was because of reduced light supply due to large canopy of the long duration varieties of pigeonpea that lead to reduced maize height and dry matter production. However the medium duration pigeonpea can be intercropped with maize without substantial maize yield loss.

N contribution through the litter fall was beneficial to subsequent maize crop, in plots previous intercropped with pigeonpea compared with continuous maize cropping. This would make a maize-pigeonpea intercrop in the first season followed by sole pigeonpea in the second season and by sole maize in the third season attractive to farmers.

6.2 Recommendations

The following recommendations can be suggested from the study.

1. Intercropping maize and long duration types of pigeonpeas in the first season followed by sole crop of pigeonpea in the second season would be more suitable to reduce competition effect because of large pigeonpea canopy in semi-arid conditions. However, the medium duration pigeonpea can be intercropped with maize without substantial maize yield loss.
2. Cotton underestimated amount of N fixed by the medium duration pigeonpea because of high biomass it accumulated. Further research is needed to identify a suitable reference crop for medium duration pigeonpea or a more reliable method can be used to determine the amount of N fixed.
3. Long duration pigeonpea took up more N from deeper layers of the soil and to a lesser extent from biological nitrogen fixation, It may play an important role in soil fertility improvement that would lead to the increase of maize yield.
4. About 62 % of N (kg/ha) taken up by pigeonpea was allocated to stems; therefore these can be incorporated back to the soil to add soil fertility rather than using them for fuel as many farmers do. However decomposition rates of the stems should be determined.
5. Long duration pigeonpea HI was low and ways of its increase should be explored to improve yields.

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APPENDICES

Appendix 1. Analysis of variance table showing MSS of root length density, root dry mass and shoot dry mass of maize, sorghum, cotton and pigeonpeas in the greenhouse (season 1 and 2) at different depths.

		Mean sum of squires (MSS)						
		Root length density (cm cm^3)			Root dry mass (g/plant)			Shoot DM
Source of variation	df	0-30 cm	0-60 cm	60-90 cm	0-30 cm	0-60 cm	60-90 cm	
Replication	4	327	9909	172.1	1.2687	0.2537	0.001869	27.93
Treatment	8	74926**	9640	172.1	13.7481**	0.2206	0.001869	186.85**
Error	32	1320	4615	172.1	0.9880	0.1251	0.001861	28.32
Total	26							
Season 2								
Replication	2	82	874	81	1.7095	0.1729	0.04871	10.04
Treatment	8	49512**	10617**	1942.7	3.5051*	0.14632	0.04565	716.96**
Error	16	1528	1310	488	0.779	0.03655	0.01981	18.35
Total	26							

***-Significant at p = 0.05, **- Significant at p = 0.01**

Appendix 2. Analysis of variance table showing MSS of nitrogen fixed by pigeon peas using cotton (Uka 59/146 and Hart 89M) as the reference crops in the field and in the greenhouse.

		Mean sum of squares (MSS)			
Source of variation	df	Field (115 DAP)	Field (220 DAP)	Greenhouse season 1	Greenhouse season 2
Replication	2	2777.0	12460	405.00	118.08
Treatment	2	28.4**	1132906*	688.55	23.20*
Reference	1	4121.3	272	34.2	1247.74
Crop. Reference	2	0	0	2.88	0
Error	10	337.4	91573	47.01	58.79
Total	17				

***- Significant at p = 0.05, **- Significant at p = 0.01**

Appendix 3. Analysis of variance table showing MSS of pigeon pea height (cm) over time.

		Mean sum of squares (MSS)								
		Days after planting (DAP)								
Source of variation	df	56	70	84	98	112	154	168	182	196
Replication	3	66	73	210.6	175.5	97.9	1521.8	131.4	189	384.8
Treatment	5	34.67	928.6*	1418.1**	1680.2**	576.5	6922.4**	6525.9**	7405.5**	13699.6**
Error	15	74.80	234.9	195.0	167	277.8	928.6	181.9	195.8	443
Total	23									

*** - Significant at p = 0.05, **- Significant at p = 0.01**

Appendix 4. Analysis of variance table showing MSS of changes of maize height (cm) in sole and intercropped in season 1 and 2.

		Mean sum of squares (MSS)								
		Days after planting (DAP)								
		Season 1				Season 2				
Source of variation	df	56	70	84	98	56	70	84	98	112
Replication	3	343.4	255.3	291.9	169.1	136.2	132.7	65.07	67.8	52.1
Treatment	3	314.2	782.5	1514.2	1908.4*	1459.4	64.2	41.11	96.7	5451.3**
Error	9	159.6	156.9	274	191.2	183.3	159.6	51.53	194.2	197.9
Total	15									

*** - Significant at p = 0.05, **- Significant at p = 0.01**

Appendix 5. Analysis of variance table showing MSS of LAI of pigeonpea at 120 and 171 DAP.

		Mean sum of squares (MSS)	
Source of variation	df	120	171
Replication	2	20.234	0.5309
Treatment	2	21.958	12.8165*
Error	4	4.043	0.4779
Total	8		

*** - Significant at p = 0.05, **- Significant at p = 0.01**

Appendix 6. Analysis of variance table showing MSS of PAR % in maize and pigeonpeas (sole and intercropped) over time.

		Mean sum of squares (MSS)										
		Days after planting (DAP)										
Source of variation	df	59	73	87	101	115	144	159	172	186	200	228
Replication	3	70.49	100.89	16.46	95.66	288.2	90.8	95.7	44.4	113.2	8.95	64.09
Treatment	6	767.69**	443.68**	301.58**	1040.84**	1276.8**	2136.0**	2980.7**	1746.7**	1482.2**	989.13**	729.83**
Error	18	45.48	62.84	48.75	98.98	176.6	287.4	108.1	120.1	152.9	98.90	22.02
Total	27											

*** - Significant at p = 0.05, **- Significant at p = 0.01**

Appendix 7. Analysis of variance table showing MSS of pigeonpea total dry matter (kg/ha) in sole and intercropped system over time.

		Mean sum of squares (MSS)									
		Days after planting (DAP)									
Source of variation	df	56	70	84	98	112	154	168	182	196	210
Replication	3	11792	98000	80172	507354	405043	7718676	4552842	3.699E+0.7	3.108E+0.7	9.607E+0.7
Treatment	5	32926	159673	310299	613093	8608212**	79641882**	100278908*	2.277E+0.8**	6.178E+0.7**	1.038E+0.7**
Error	15	13095	95690	121466	292824	327455	8602724	17374006	2.569E+0.7	4.067E+0.7	6.742E+0.7
Total	23										

*** - Significant at p = 0.05, **- Significant at p = 0.01**

Appendix 8. Analysis of variance table showing MSS of maize total dry matter (kg/ha) in sole and intercropped system over time.

		Mean sum of squares (MSS) Days after planting (DAP)									
Source of variation	df	56	70	84	98	112	154	168	182	196	210
Replication	3	6429	316973	115891	234650	5090096	301	6954	260788	778602	1226421
Treatment	3	2276.1*	844184*	659916	2933338*	5116095	45174*	196777*	438080	1519036	4813262
Error	9	449.0	185749	222989	372903	3273598	6721	21194	156217	7361660	4469154
Total	15										

*** - Significant at p = 0.05, **- Significant at p = 0.01**

Appendix 9. Analysis of variance table showing MSS of the maize crop growth rate.

		Mean sum of squares (MSS)			
		Days after planting (DAP)			
Source of variation	df	60-74	74-88	88-102	102-115
Season 1					
Replication	3	91.5	236.6	1467.9	20349
Treatment	3	1704.3*	2252.6*	4380.6*	2118
Error	7	239.2	473.0	913.5	17360
Total	13				
Season 2					
Replication	3	11.44	1579.2	7999	1745
Treatment	3	192.73*	1197.9	3134	375
Error	7	27.86	770.4	4412	3797
Total	13				

*** - Significant at p = 0.05, **- Significant at p = 0.01**

Appendix 10. Analysis of variance table showing MSS of pigeonpea crop growth rate.

		Mean sum of squares (MSS)					
		Days after planting (DAP)					
Source of variation	df	60-74	74-88	88-102	102-115	115-159	159-172
Replication	3	520.0	70.4	760.4	699	24026	34763
Treatment	5	311.8	284.8	550.5	17976*	181340*	18050
Error	15	316.1	117.3	715.9	1239	34130	52267
Total	29						

*** - Significant at p = 0.05, **- Significant at p = 0.01**

Appendix 11. Analysis of variance table showing MSS of stored water over time of maize and pigeonpea in the sole and intercrop.

		Mean sum of squares (MSS) Days after planting (DAP)														
Source of variation	df	31	45	59	73	87	101	116	130	144	159	172	186	200	214	228
Replication	3	627.17	76.7	630	153.4	120.5	76.1	266.0	246.2	222.43	455.3	338.9	219.1	292.19	609.1	38.8
Treatment	9	66.17	72.9	319.7	93.5	154.8	89.3	413.8*	296.7*	309.45**	415.6*	359.1*	475.8	69.88	485.1	331.6
Error	27	80.9	100.1	359.4	147.5	115.1	102.5	149.8	102.8	59.05	123.8	159.3	374	98.98	658.4	134.1
Total	39															

***- Significant at p = 0.05, **- Significant at p = 0.01**

Appendix 12. Analysis of variance table showing MSS of cumulative evapotranspiration over time of maize and pigeonpea in the sole and intercrop system.

		Mean sum of squares (MSS) Days after planting (DAP)								
Source of variation	df	45	59	73	87	101	115	130	144	159
Replication	3	349.2	201.66	690.3	905.4	1352.6	750.7	647.4	755.11	471.57
Treatment	9	50.54	97.38	407.1	426.7	249.9	508.3	204.7	102643.08**	104931.13**
Error	27	77.82	95.09	310.8	231.7	385.6	329.8	126.5	73.98	98.53
Total	39									
DAP cont"		172	186	200	214	228				
Replication	3	498.95	1088.5	480.10	267.3	954.3				
Treatment	9	102087.92**	93653.5**	99180.79**	95619.9**	102150**				
Error	27	89.14	474.6	65.18	514.9	111.1				
Total	39									

*** - Significant at p = 0.05, **- Significant at p = 0.01**

Appendix 13. Analysis of variance table showing MSS of fallen leaves and total N kg/ha in sole and intercropped system of pigeonpea.

		Mean sum of squares (MSS)	
Source of variation	df	Total leaves	Total N kg/ha
Replication	2	6430	833.6
Treatment	5	129250**	2540.5*
Error	10	7316	669.3
Total	17		

***- Significant at p = 0.05, **- Significant at p = 0.01**

Appendix 14. Analysis of variance table showing MSS of N uptake (kg/ha) and [N] for maize in stems (ST), cobs (CB) and grains (GR) and harvest index (HI) at 115 DAP and 220 DAP.

		Mean sum of squares (MSS)										
Source of variation	df	CB DM	CB [N]	T CB N	GR DM	GR [N]	T GR N	ST DM	ST [N]	T ST N	TOTAL N	HI
Replication	2	1919	0.00011	0.261	225850	0.02556	97.43	41991550	0.006908	82.4	191.2	0.05040
Treatment	3	148428	0.02209	7.005	1550619	0.143442	27.35	125137	0.002764	54.41	132.4	0.01482
Error	6	22537	0.01786	2.246	409495	0.6445	53.21	1193670	0.005664	46.71	164.6	0.01598
Total	11											
220 DAP												
Rep	2	463	0.5227	3.852	151723	0.2335	730.1	252130	0.026	51	13304	0.000715
Tmt	3	8175	0.0324	1.050	1058107	0.1986	8171.1	231989	0.4174	238.7	416729	0.017979
Error	6	2013	0.7999	5.341	232787	0.2044	686.9	773028	0.9489	427.4	26899	0.005074
Total	11											

*** - Significant at p = 0.05, **- Significant at p = 0.01**

Appendix 15. Analysis of variance table showing MSS of N uptake for pigeonpea at 115 DAP in the sole and intercrop.

		Mean sum of squares (MSS)	
Source of variation	df	DM	[N]
Replication	2	601548	0.04642
Treatment	5	5663159	0.01485
Error	10	394679	0.032330
Total	17		

*** - Significant at p = 0.05, **- Significant at p = 0.01**

Appendix 16. Analysis of variance table showing MSS of N uptake (kg/ha) and [N] of husks (HK), stems (ST) and grains (GR) in pigeonpea at 220 DAP.

		Mean sum of squares (MSS)										
Source of variation	df	HK DM	HK [N]	T HK N	GR DM	GR [N]	T GR N	ST DM	ST [N]	T ST N	TOTAL N	HI
Replication	2	5790	0.05217	4.287	424955	0.0091	1309	2.297E+07	0.2493	20345	15697	0.000833
Treatment	5	458443**	0.03482	72.147**	2533350*	1.6950*	5115*	7.100E+0.8**	0.2423	338831**	382167**	0.034054**
Error	10	6185	0.03565	1.823	332538	0.2103	1377	1.963E+07	0.2262	26331	25089	0.003935
Total	17											

***- Significant at p = 0.05, **- Significant at p = 0.01**

Appendix 17. Analysis of variance table showing MSS of soil mineral N at the middle of the season (115 DAP) and end season (220 DAP) in sole and intercropped plots of pigeonpea at different depths.

		Mean sum of squares (MSS)					
		Middle season (115 DAP)			End season (220DAP)		
Source of variation	df	0-20 cm	20-50 cm	50-100 cm	0-20 cm	20-50 cm	50-100 cm
Replication	2	7366	182334	40306	56294	33465	39497
Treatment	6	1926	5612	27126	109725	34791	3970
Error	12	1653	8085	22479	146222	46372	10586
Total	20						

*** - Significant at p = 0.05, **- Significant at p = 0.01**

Appendix 18. Analysis of variance table showing MSS of the residual effect on subsequent maize in stems, grains and cobs N uptake, total N uptake, total dry matter accumulation and soil N %.

		Mean sum of squares (MSS)								
		Nitrogen				Dry matter				
Source of variation	df	Cob	Grain	Stem	Total N	Cob	Grain	Stem	Total Dry matter	Soil N %
Replication	2	25.326	428.37	63.78	1255.5	106738	1554546	246068	5057432	0.0001274
Treatment	6	4.040	188.71	76.72	431.2	282554	384806	295963	1678818	0.0005369
Error	8	1.507	67.33	34.14	199.7	11674	244350	131707	728050	0.0005940
Total	16									

*** - Significant at p = 0.05, **- Significant at p = 0.01**